Massive graviton dark matter searches with atom interferometers

John Carlton
john.carlton@kcl.ac.uk

Based on arXiv: 2412.14282

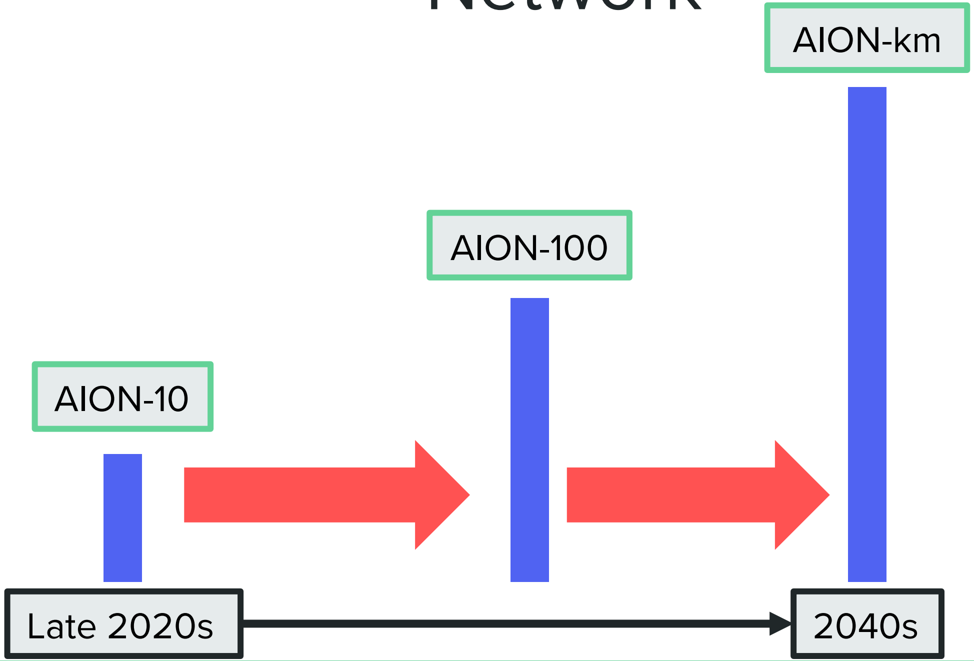
AION

KING'S College LONDON

AION

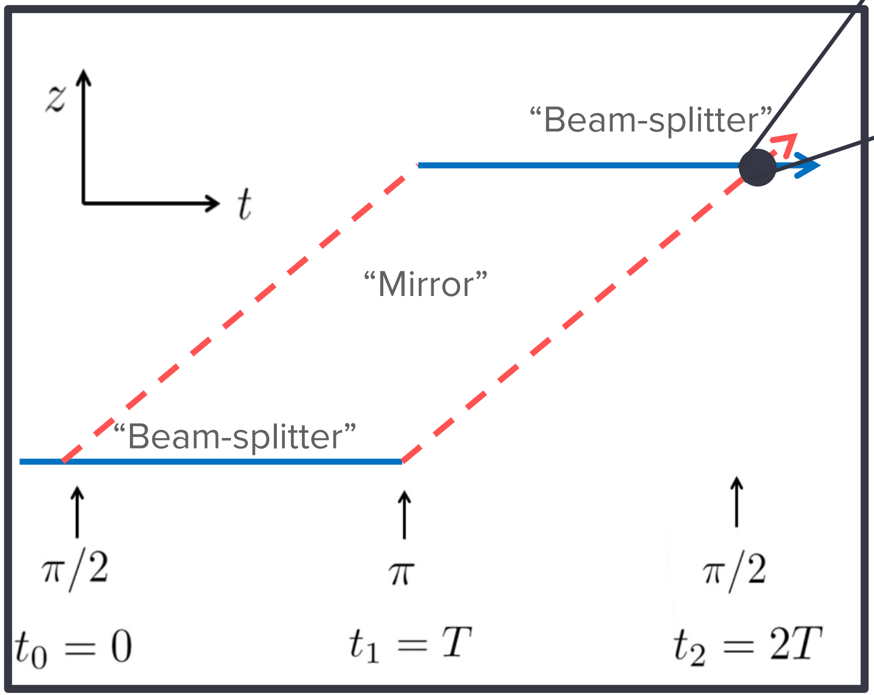
Atom Interferometer Observatory and Network

arXiv: 1911.11755



Atom interferometry

Interferometer sequence



Mach-Zehnder interferometer

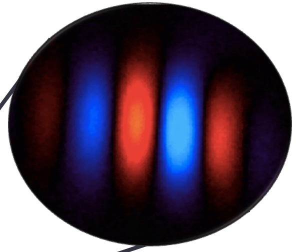


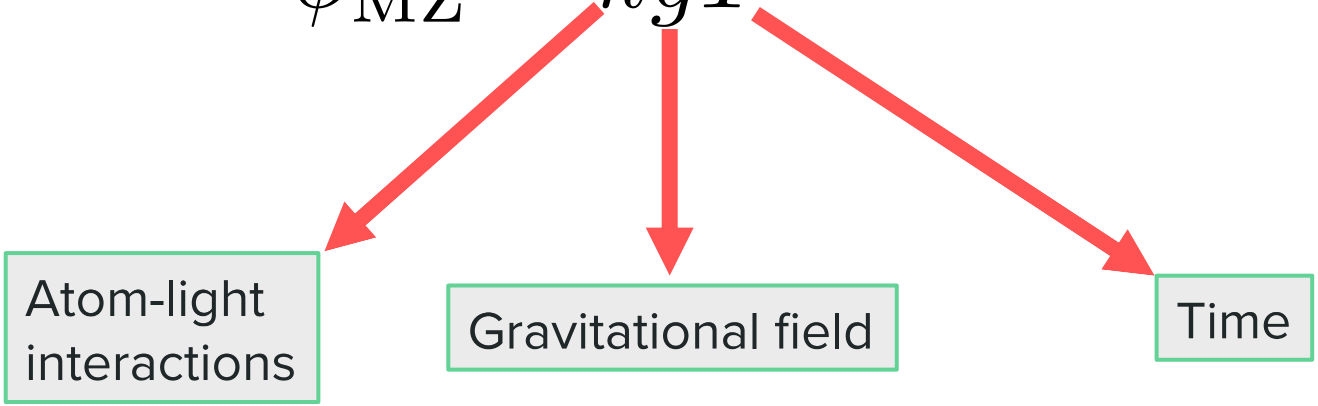
Image atom fringes and measure phase

$$\phi_{\mathrm{MZ}} = kgT^2$$

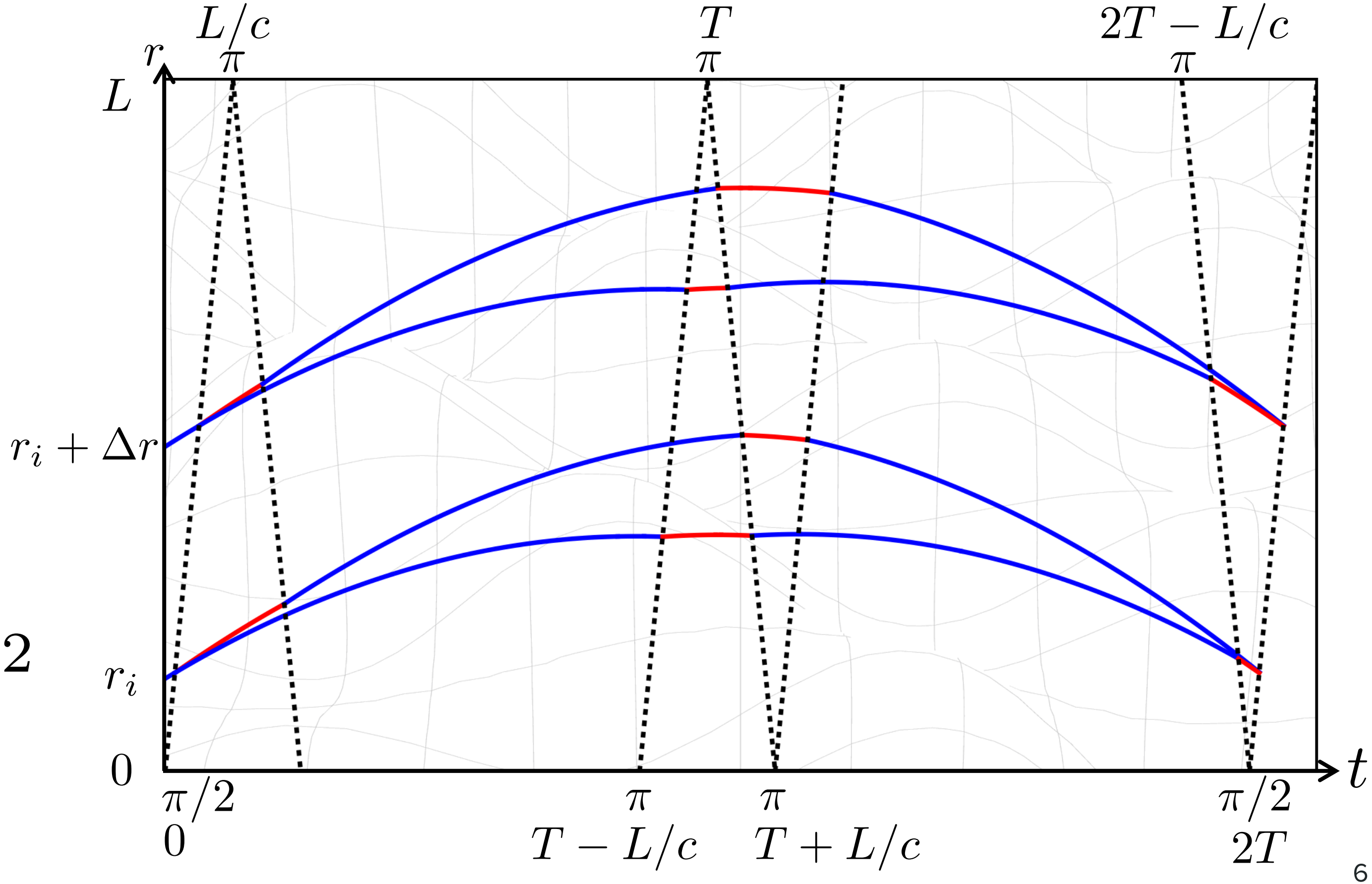
Leading order phase depends on gravitational acceleration

What can we measure?

$$\phi_{\mathrm{MZ}} = kgT^2$$

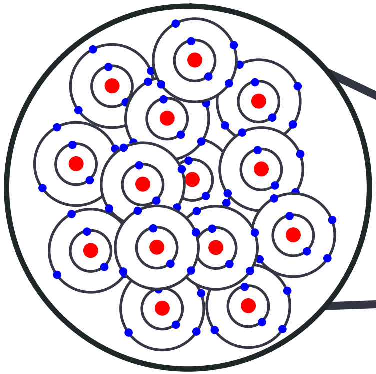


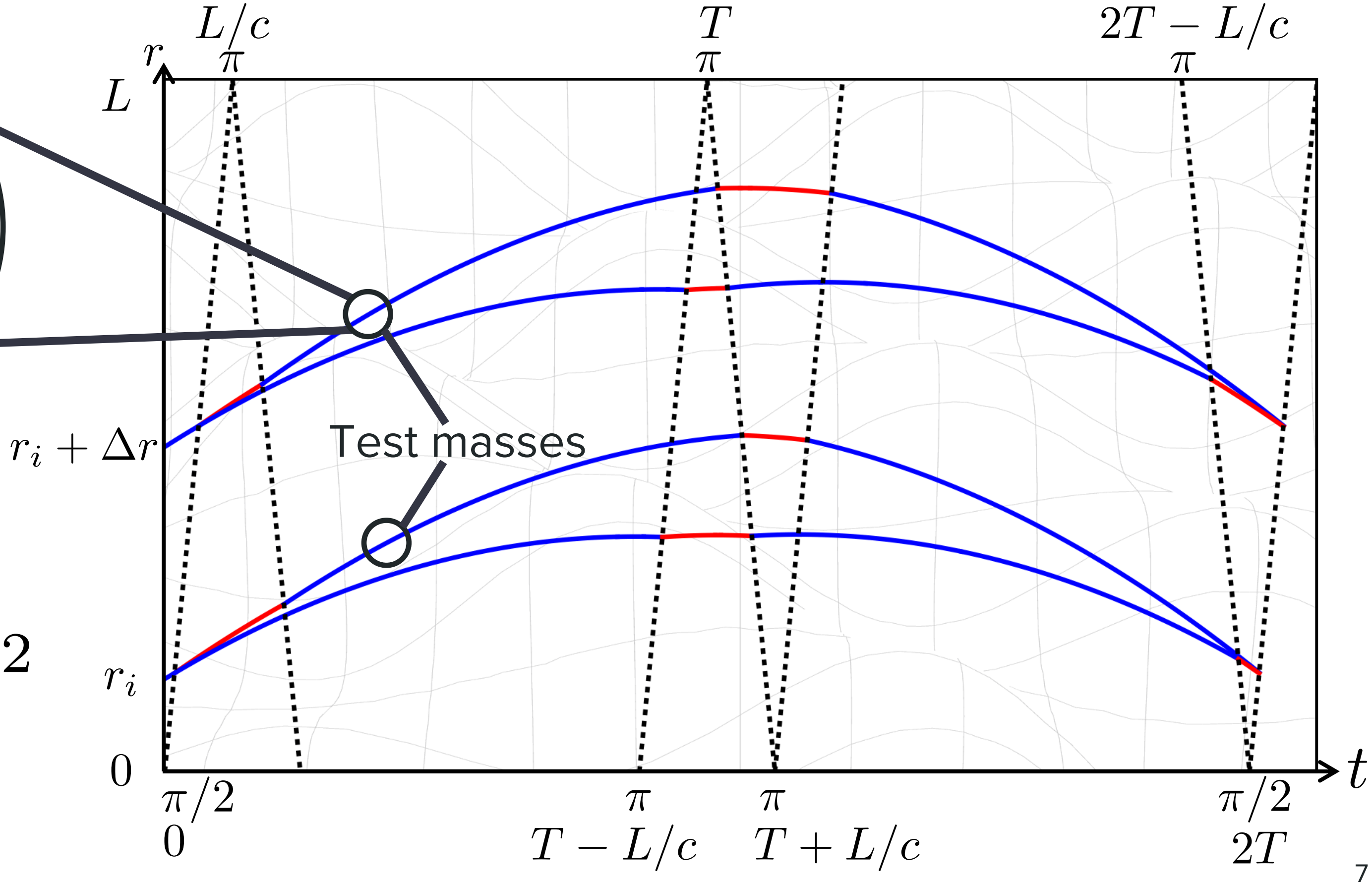
Atom gradiometer



Gradiometer phase

$$\Delta\phi = \phi_1 - \phi_2$$





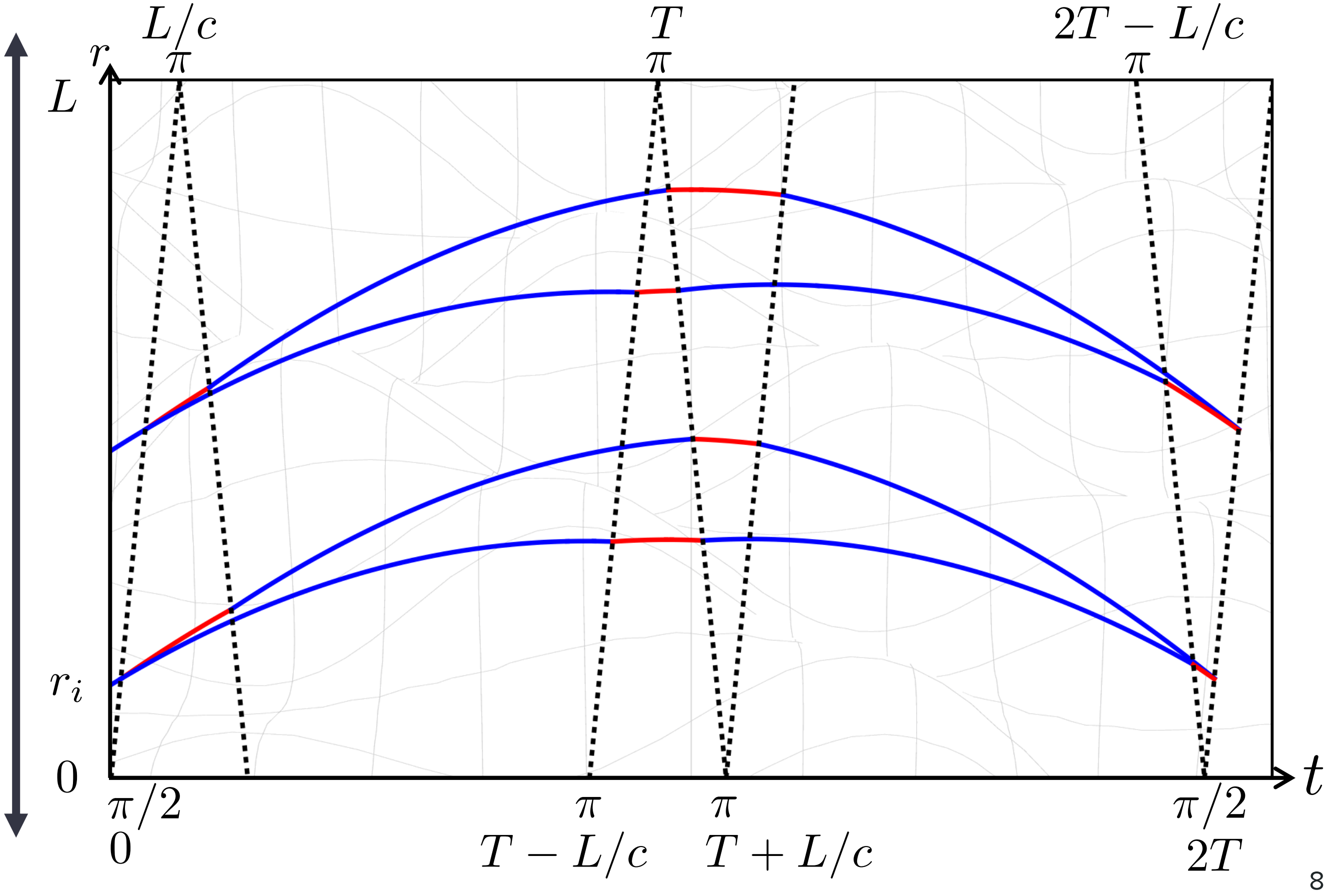
Gradiometer phase

$$\Delta\phi = \phi_1 - \phi_2$$

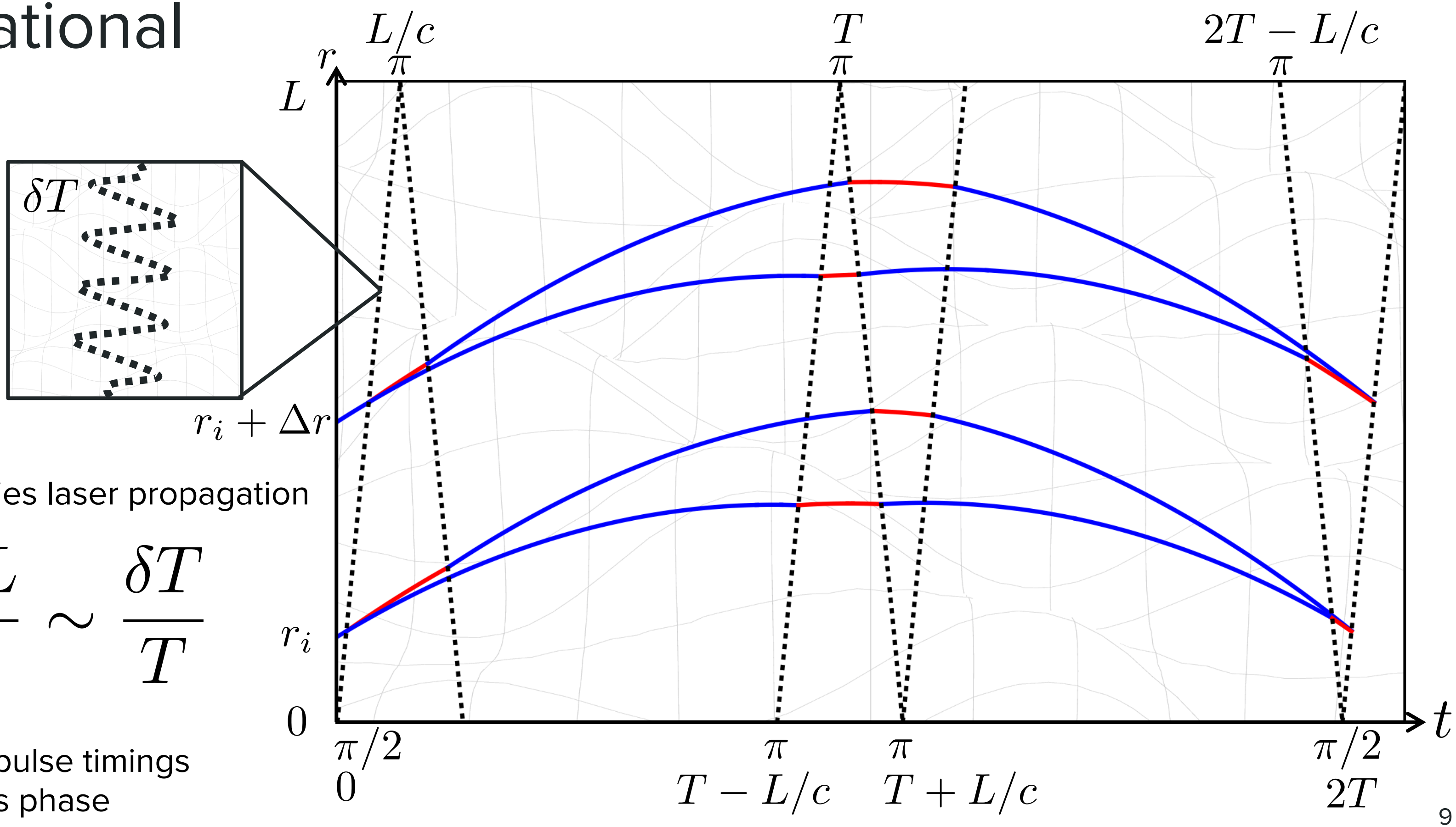
Longer baseline L

Longer time of flight T

More sensitivity $\Delta\phi$



Gravitational waves

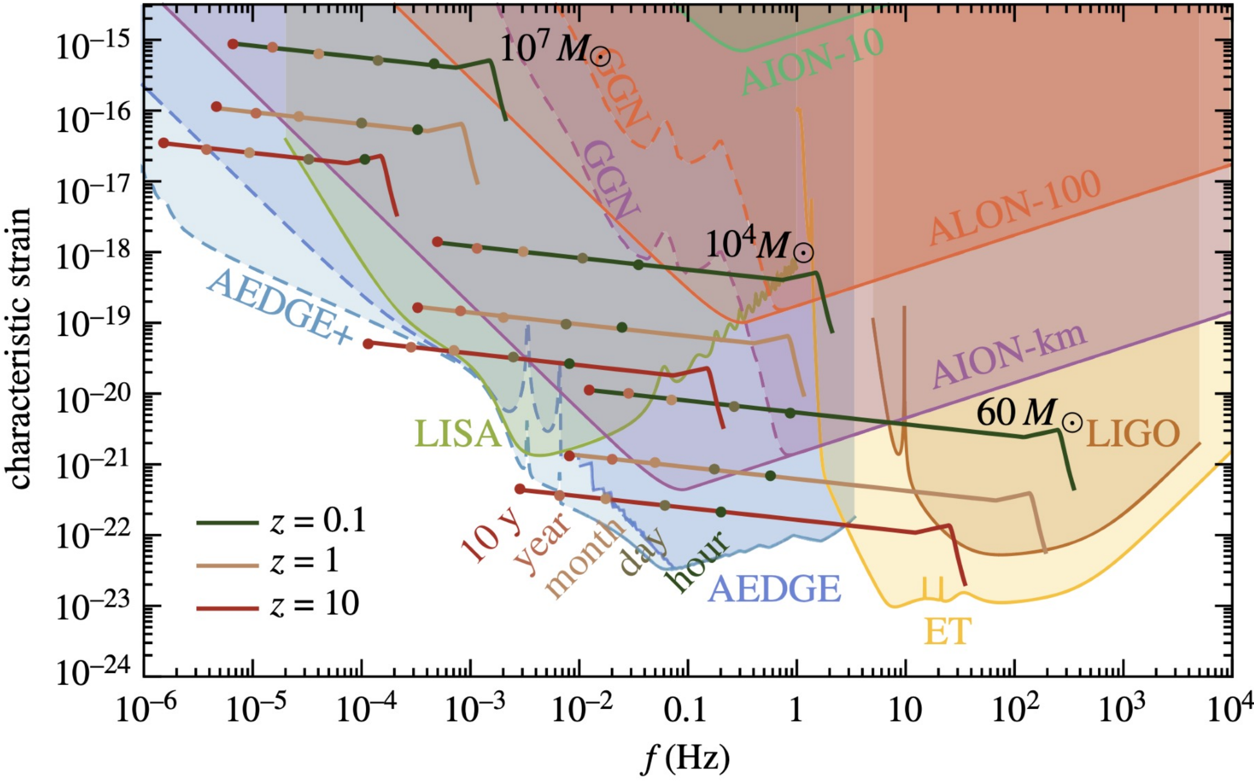


GW strain modifies laser propagation

$$h \sim \frac{\delta L}{L} \sim \frac{\delta T}{T}$$

Change in pulse timings affects phase

Gravitational waves

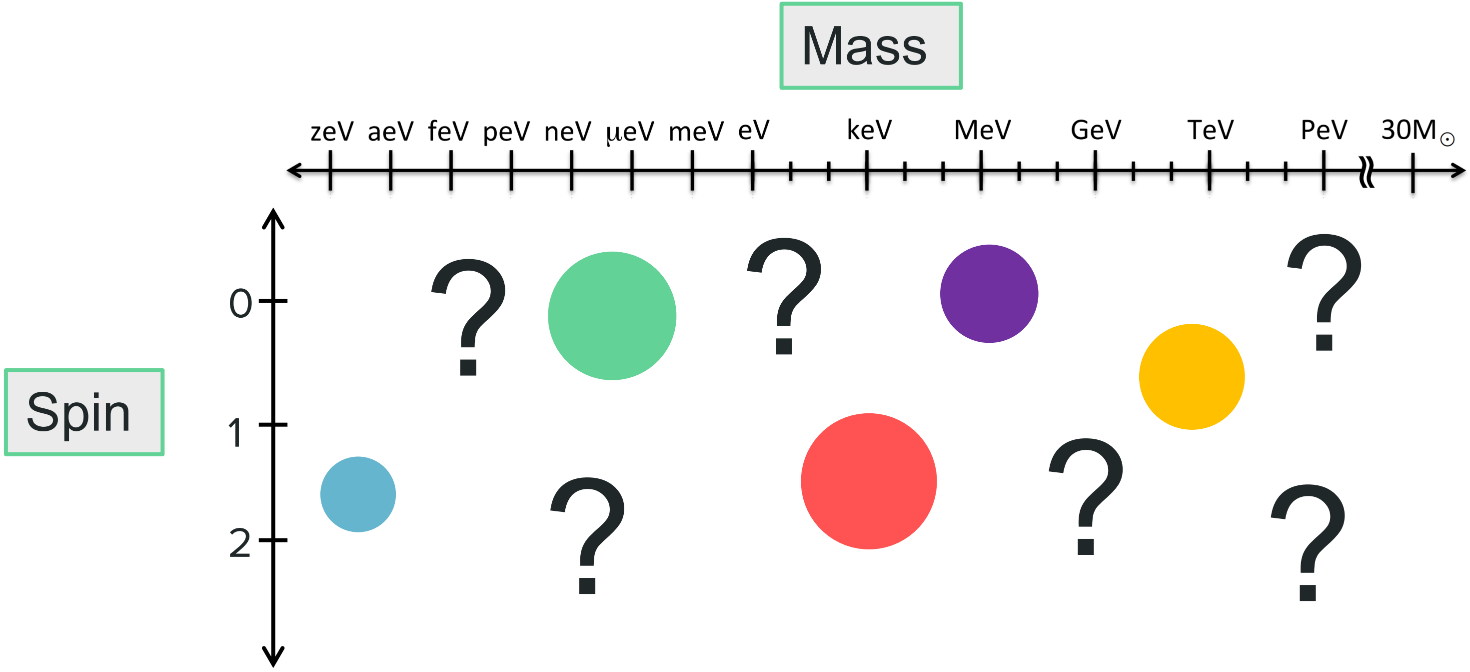


- ‘Mid-band’ sensitivity between LIGO and LISA.

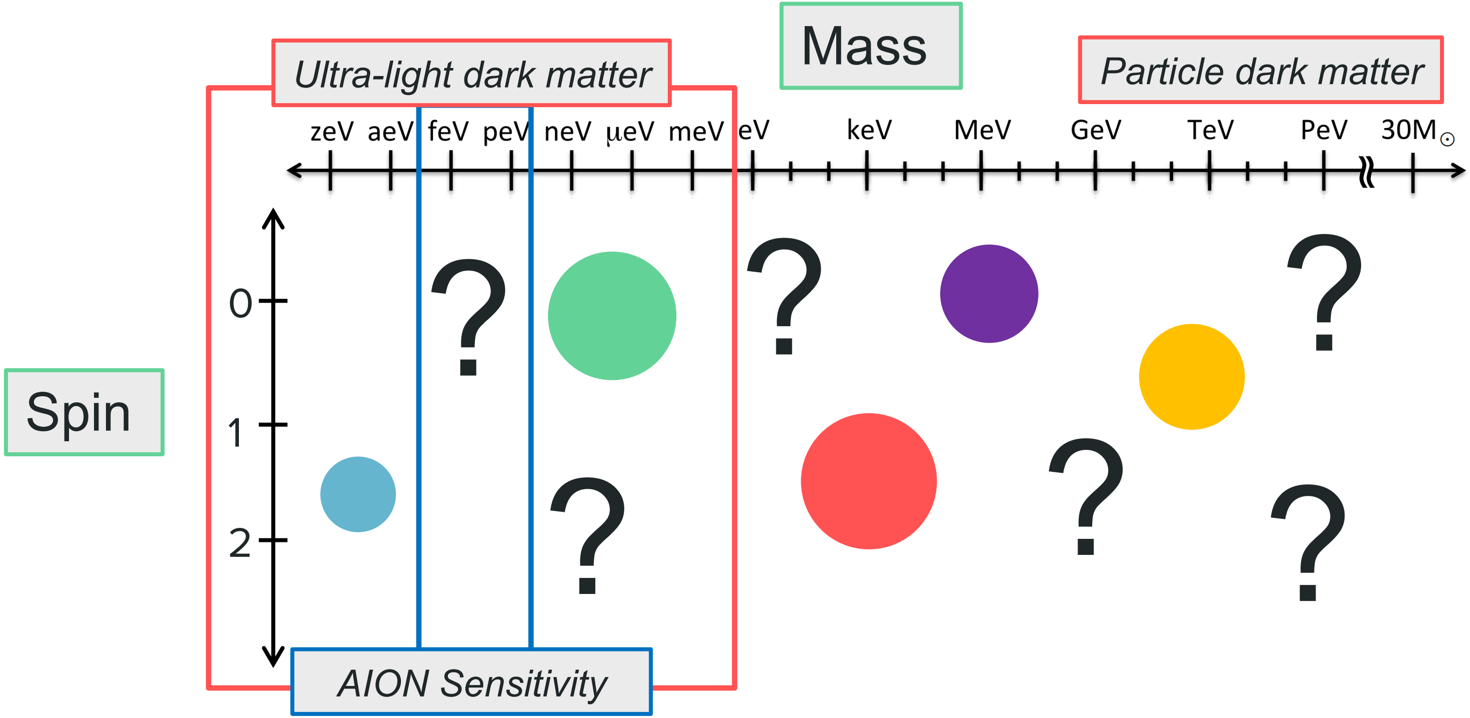
L. Badurina et al. arXiv: 2108.02468

Dark matter

A lot of parameter space!



A lot of parameter space!



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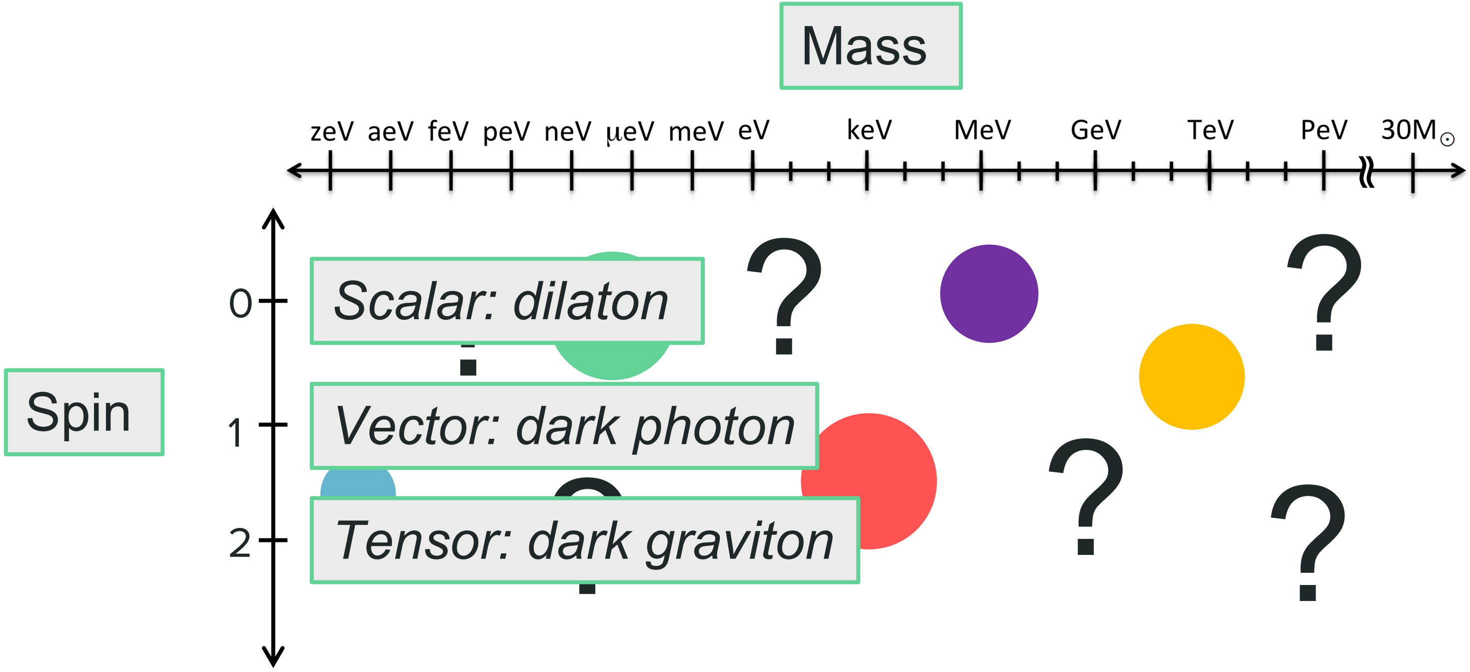
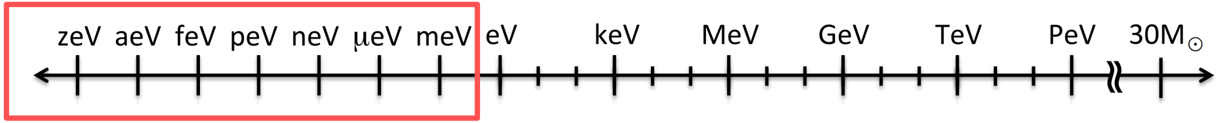


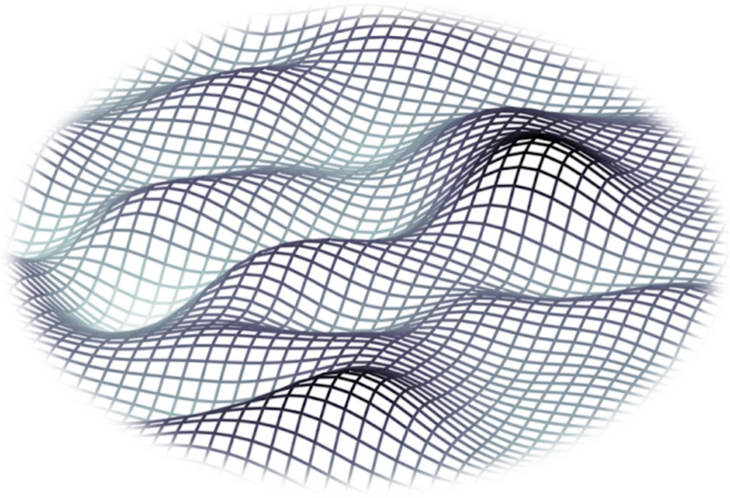
A classical ULDM field



Ultralight mass means a high occupation number

Can describe as a classical field

$$\varphi(t, \mathbf{x}) \sim \cos(\omega_\varphi t - \mathbf{k}_\varphi \cdot \mathbf{x})$$



Frequency given by ULDM mass
(with small velocity correction)

$$\omega_\varphi \simeq m_\varphi \left(1 + \frac{v^2}{2}\right)$$

Badurina et al. arxiv: 2109.10965

Atoms in a scalar ULDM field

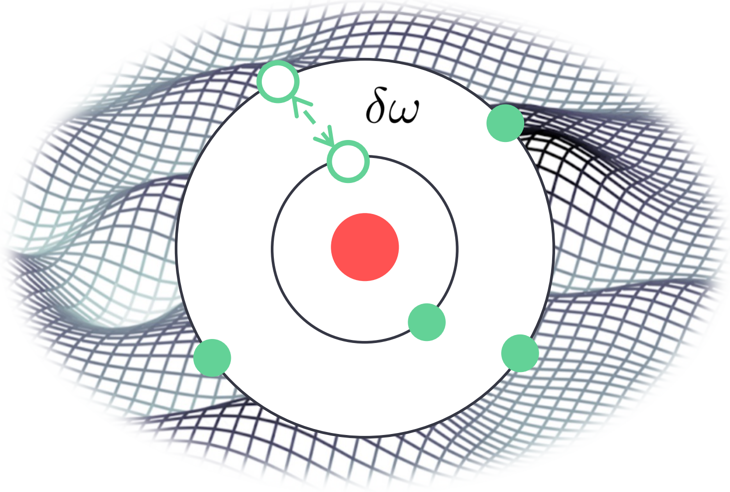
photon coupling   electron coupling

$$\mathcal{L} \supset \mathcal{L}_{\rm SM} + \mathcal{L}_\varphi \quad \longrightarrow \quad \mathcal{L}_\varphi \supset \varphi(t,\boldsymbol{x})\sqrt{4\pi G_{\rm N}}\left[\frac{d_e}{4e^2}F_{\mu\nu}F^{\mu\nu} - d_{m_e} m_e \bar{\psi}_e \psi_e\right]$$

$$\alpha(t,\boldsymbol{x}) \approx \alpha\left[1 + d_e\sqrt{4\pi G_{\rm N}}\,\varphi(t,\boldsymbol{x})\right],$$

$$m_e(t,\boldsymbol{x}) = m_e\left[1 + d_{m_e}\sqrt{4\pi G_{\rm N}}\,\varphi(t,\boldsymbol{x})\right]$$

$$\delta\phi \sim \delta\omega \sim \varphi(t,\boldsymbol{x})$$



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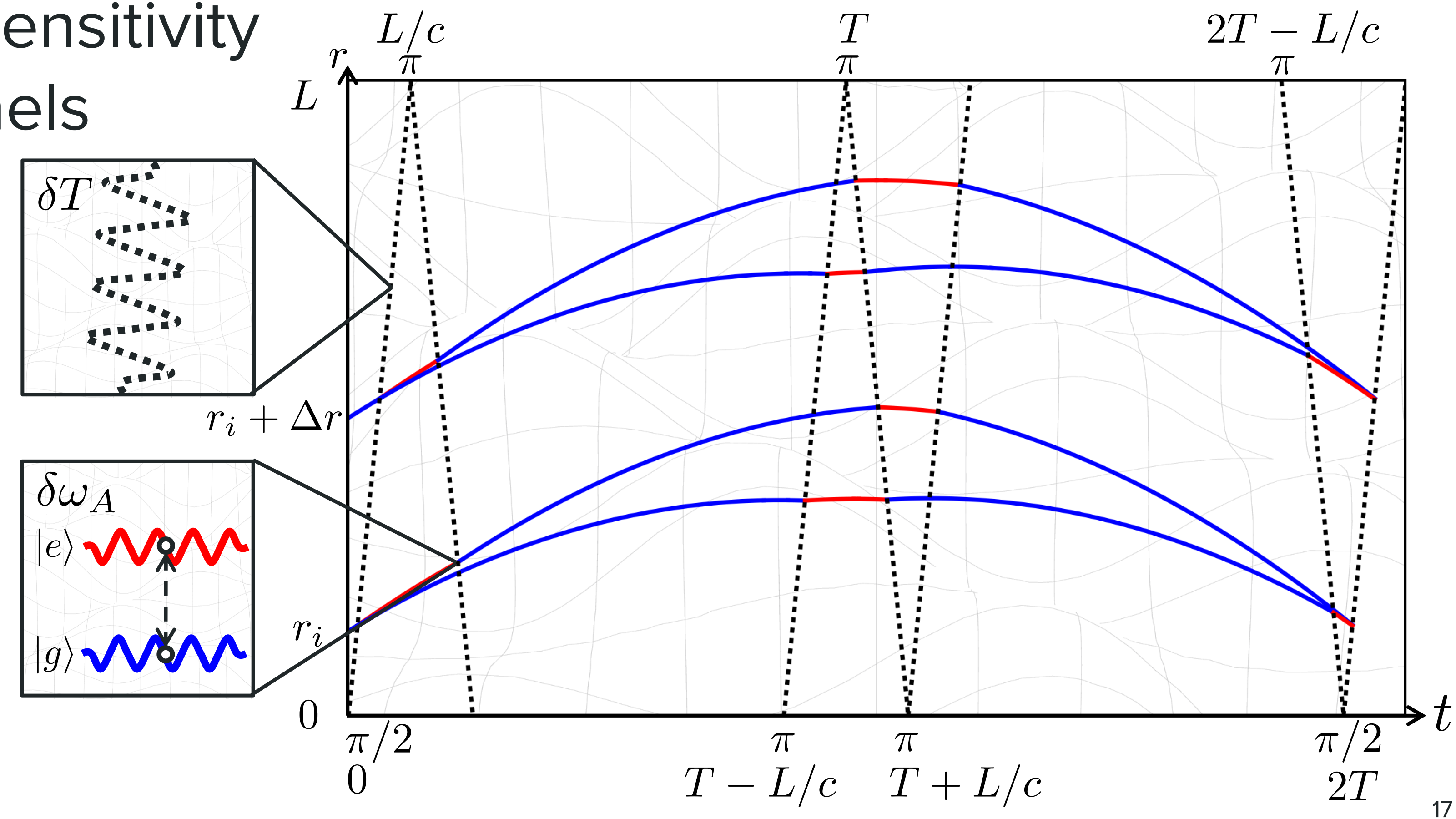
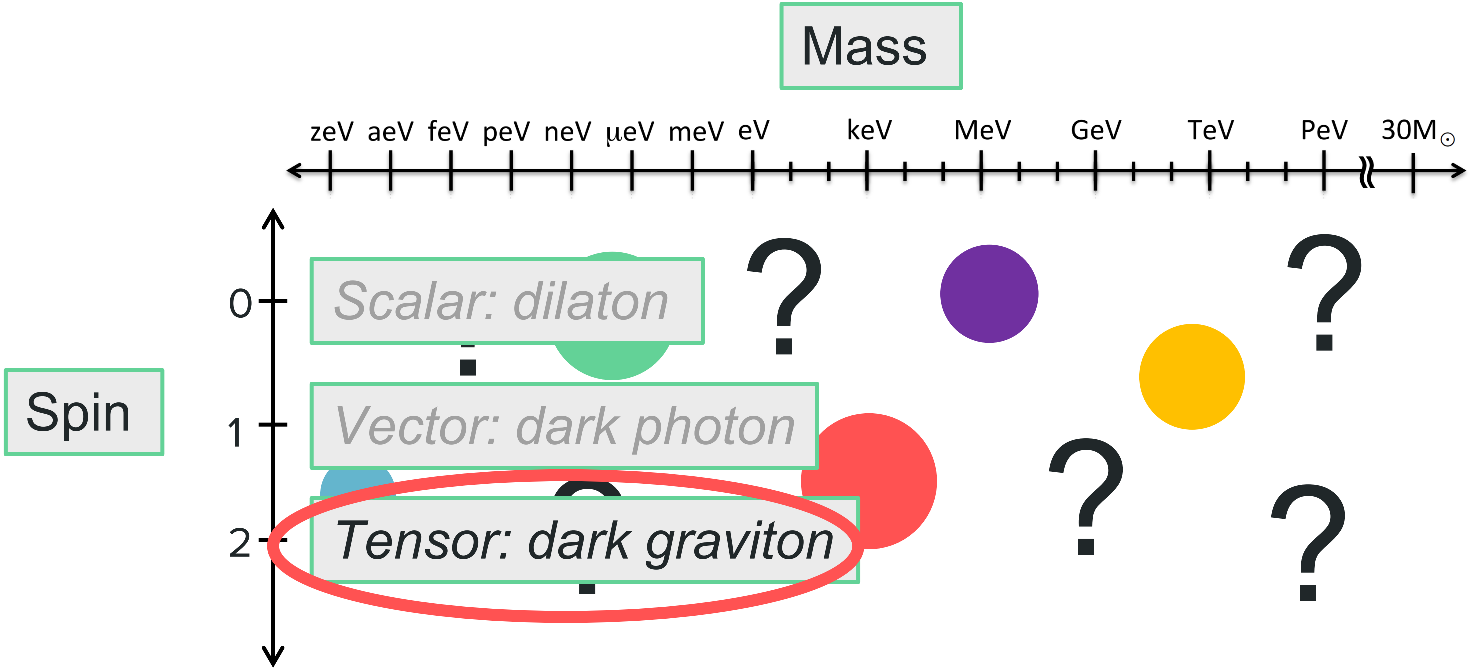
Two sensitivity channels

Interrogation time (GWs)

Atomic transition frequency (Scalar ULDM)



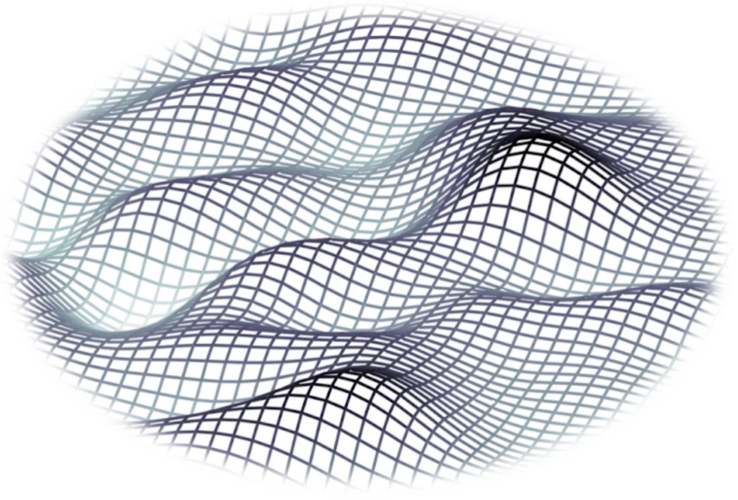
What about spin-2?



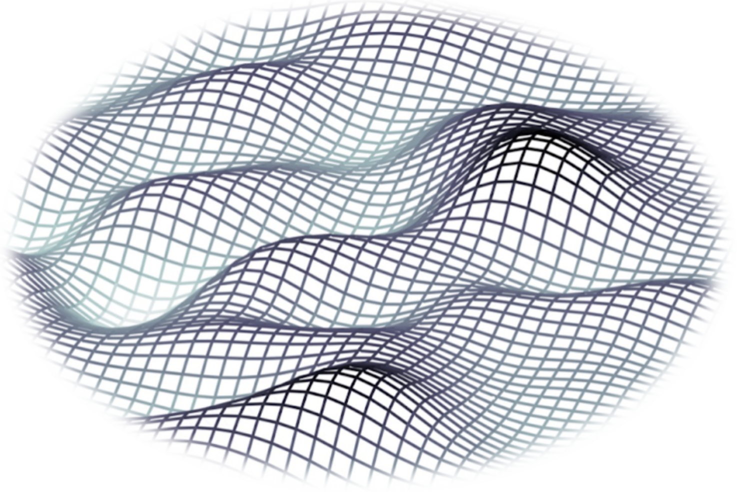
Massive graviton dark matter

Massive gravity field theory

Let's consider a massive spin-2 ultra-light field $\varphi_{\mu\nu}$



Massive gravity field theory



Let's consider a massive spin-2 ultra-light field $\varphi_{\mu\nu}$

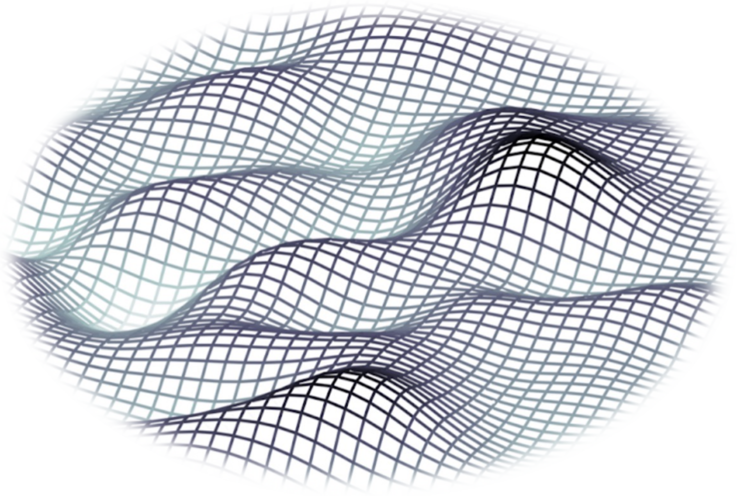
Express as irreducible fields:

$$\varphi_{00} = \Psi$$

$$\varphi_{0i} = u_i + \partial_i v$$

$$\varphi_{ij} = \varphi_{ij}^{\mathrm{TT}} + 2\partial_{(i}A_{j)} + \partial_i\partial_j\sigma + \delta_{ij}\pi$$

Massive gravity field theory



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Tensor

Vector

Scalar

Three normalised fields

Tensor $$\mathcal{L}_t = \frac{1}{2}\left(\widetilde{\varphi}_{ij}\Box\widetilde{\varphi}_{ij} - m_t^2\widetilde{\varphi}_{ij}\widetilde{\varphi}_{ij}\right)$$

Vector $$\mathcal{L}_v = \frac{1}{2}\left(\widetilde{A}_i\Box\widetilde{A}_i - m_v^2\widetilde{A}_i\widetilde{A}_i\right)$$

Scalar $$\mathcal{L}_s = \frac{1}{2}\left(\widetilde{\pi}\Box\widetilde{\pi} - m_s^2\widetilde{\pi}^2\right)$$

Coupling to light and matter

$$\mathcal{L}_{\rm int} = \kappa^{\phi} \varphi^{\mu\nu} \mathcal{O}_{\mu\nu}$$

↑

Symmetric Standard Model operator

Coupling to light and matter

Tensor Vector Scalar

$$\mathcal{L}_{\text{int}} = \kappa^{\phi} \varphi^{\mu\nu} \mathcal{O}_{\mu\nu} \longrightarrow \kappa_t \varphi^{ij} \mathcal{O}^t_{ij} + \kappa_v \varphi^{0i} \mathcal{O}^v_{0i} + \kappa_s \varphi^{00} \mathcal{O}^s$$

Coupling to light and matter

Tensor — Vector — Scalar

$$\mathcal{L}_{\text{int}} = \kappa^{\phi} \varphi^{\mu\nu} \mathcal{O}_{\mu\nu} \longrightarrow \kappa_t \varphi^{ij} \mathcal{O}^t_{ij} + \kappa_v \varphi^{0i} \mathcal{O}^v_{0i} + \kappa_s \varphi^{00} \mathcal{O}^s$$

Non-relativistic limit

$$\frac{\beta^{(2)}}{\Lambda} \varphi^{\text{TT}}_{ij} F^{i\sigma} F^{j}_{\sigma} \qquad \left(\frac{\beta^{(0)}}{\Lambda} F^2 + m_\psi \frac{\alpha^{(0)}}{\Lambda} \overline{\psi}\psi \right) \widetilde{\pi}$$

Coupling to light and matter

Tensor — Vector — Scalar

$$\mathcal{L}_{\text{int}} = \kappa^{\phi}\varphi^{\mu\nu}\mathcal{O}_{\mu\nu} \longrightarrow \kappa_t \varphi^{ij}\mathcal{O}^t_{ij} + \kappa_v \varphi^{0i}\mathcal{O}^v_{0i} + \kappa_s \varphi^{00}\mathcal{O}^s$$

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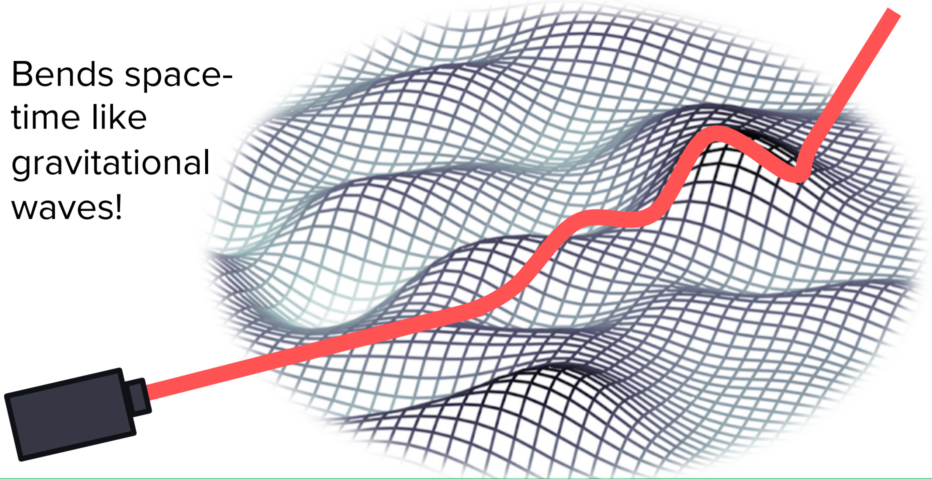
In all theories — Only in Lorentz violating theories!

Coupling to light and matter

Tensor modes

$$\frac{\beta^{(2)}}{\Lambda}\varphi_{ij}^{\mathrm{TT}}F^{i\sigma}F^{j}_{\sigma}$$

Bends space-time like gravitational waves!



Coupling to light and matter

Tensor modes

$$\frac{\beta^{(2)}}{\Lambda}\varphi_{ij}^{\mathrm{TT}}F^{i\sigma}F_{\sigma}^{j}$$

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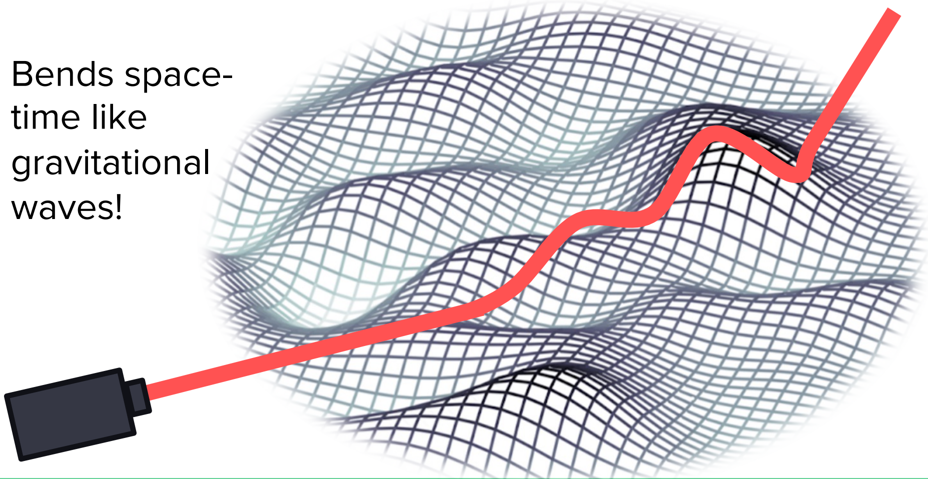
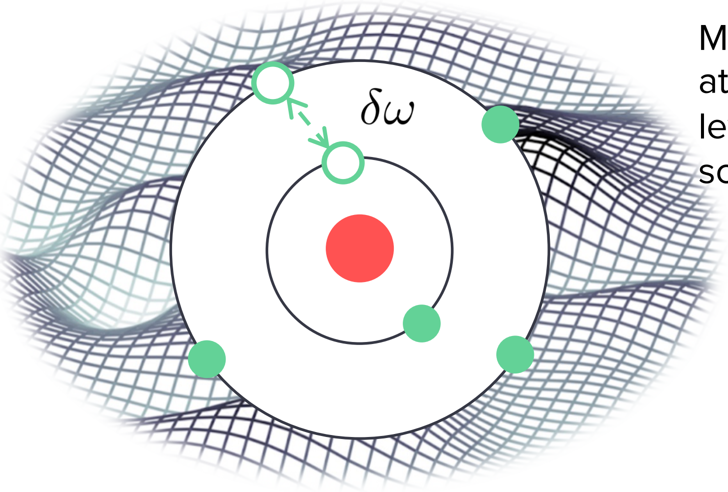


Scalar modes

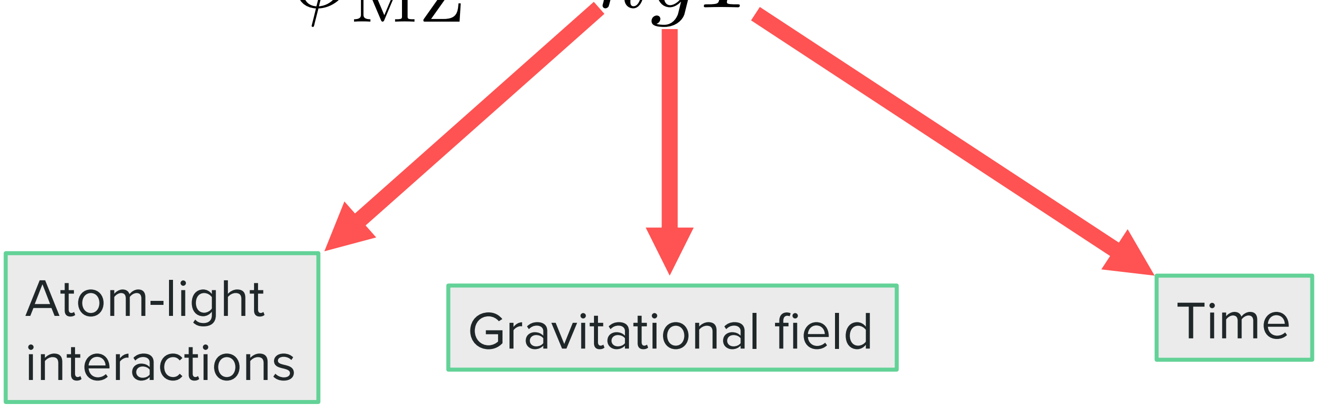
$$\left(\frac{\beta^{(0)}}{\Lambda}F^2+m_\psi\frac{\alpha^{(0)}}{\Lambda}\overline{\psi}\psi\right)\tilde{\pi}$$



Modifies atomic energy levels just like scalar ULDM!

What can we measure?

$$\phi_{\mathrm{MZ}} = kgT^2$$



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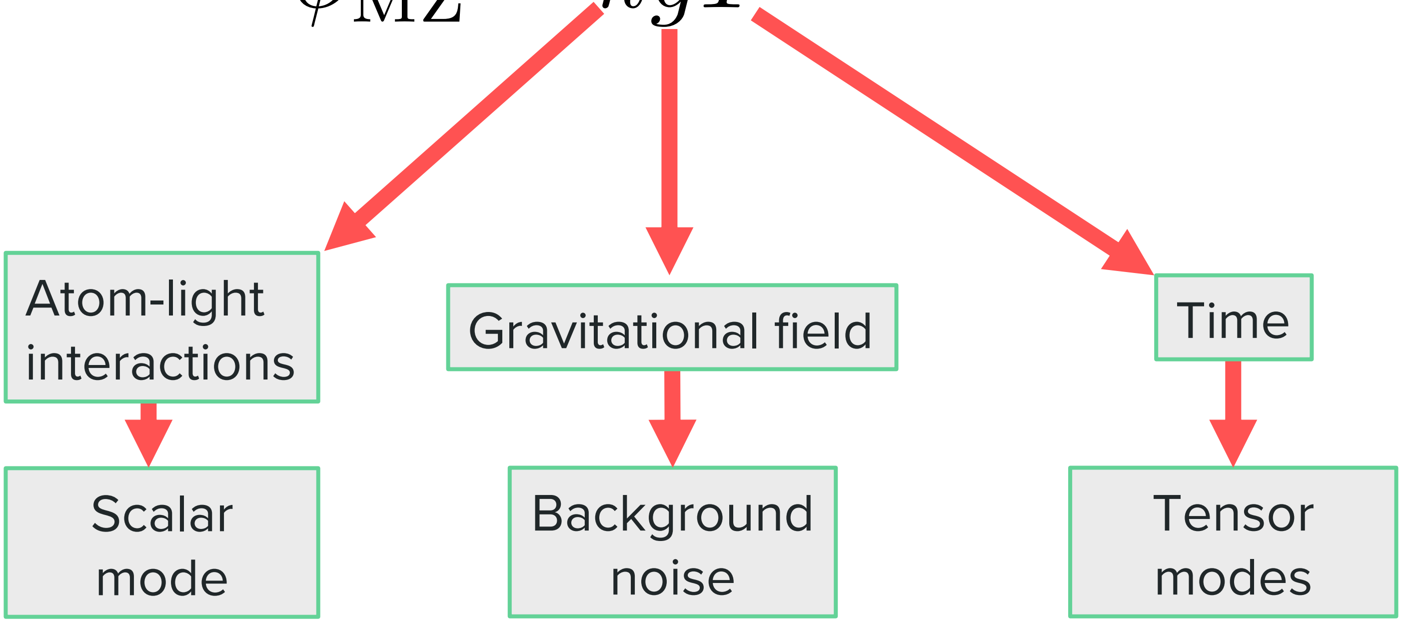


Other couplings

$$\mathcal{H} = \sqrt{\rho_{\rm DM}}\left(\frac{\alpha^{(0)}}{\Lambda}X(t) + \frac{\alpha^{(1)}}{\Lambda}v_A^i V_i(t) + \frac{\alpha^{(2)}}{\Lambda}v_A^i v_A^j M_{ij}(t)\right) m_A \delta^{(3)}(\vec{x} - \vec{x}_A(t))$$
$$+ \sqrt{\rho_{\rm DM}}\left(\frac{\beta^{(0)}}{\Lambda}(F^2 Y_1(t) + F_{0i}F^{0i}Y_2(t)) + \frac{\beta^{(1)}}{\Lambda}F_{\sigma 0}F^{i\sigma}W_i(t) + \frac{\beta^{(2)}}{\Lambda}F^{i\sigma}F_\sigma^j N_{ij}(t)\right)$$

D. Blas, J. Carlton, C. McCabe. arXiv: 2412.14282

Other couplings

Matter couplings

Electron mass variation

$$\mathcal{H} = \sqrt{\rho_{\rm DM}}\left(\frac{\alpha^{(0)}}{\Lambda}X(t) + \frac{\alpha^{(1)}}{\Lambda}v_A^i V_i(t) + \frac{\alpha^{(2)}}{\Lambda}v_A^i v_A^j M_{ij}(t)\right) m_A \delta^{(3)}(\vec{x} - \vec{x}_A(t))$$

$$+ \sqrt{\rho_{\rm DM}}\left(\frac{\beta^{(0)}}{\Lambda}(F^2 Y_1(t) + F_{0i}F^{0i}Y_2(t)) + \frac{\beta^{(1)}}{\Lambda}F_{\sigma 0}F^{i\sigma}W_i(t) + \frac{\beta^{(2)}}{\Lambda}F^{i\sigma}F^j_\sigma N_{ij}(t)\right)$$

Fine structure variation

Light couplings

Laser propagation delay

D. Blas, J. Carlton, C. McCabe. arXiv: 2412.14282

Other couplings

Matter couplings

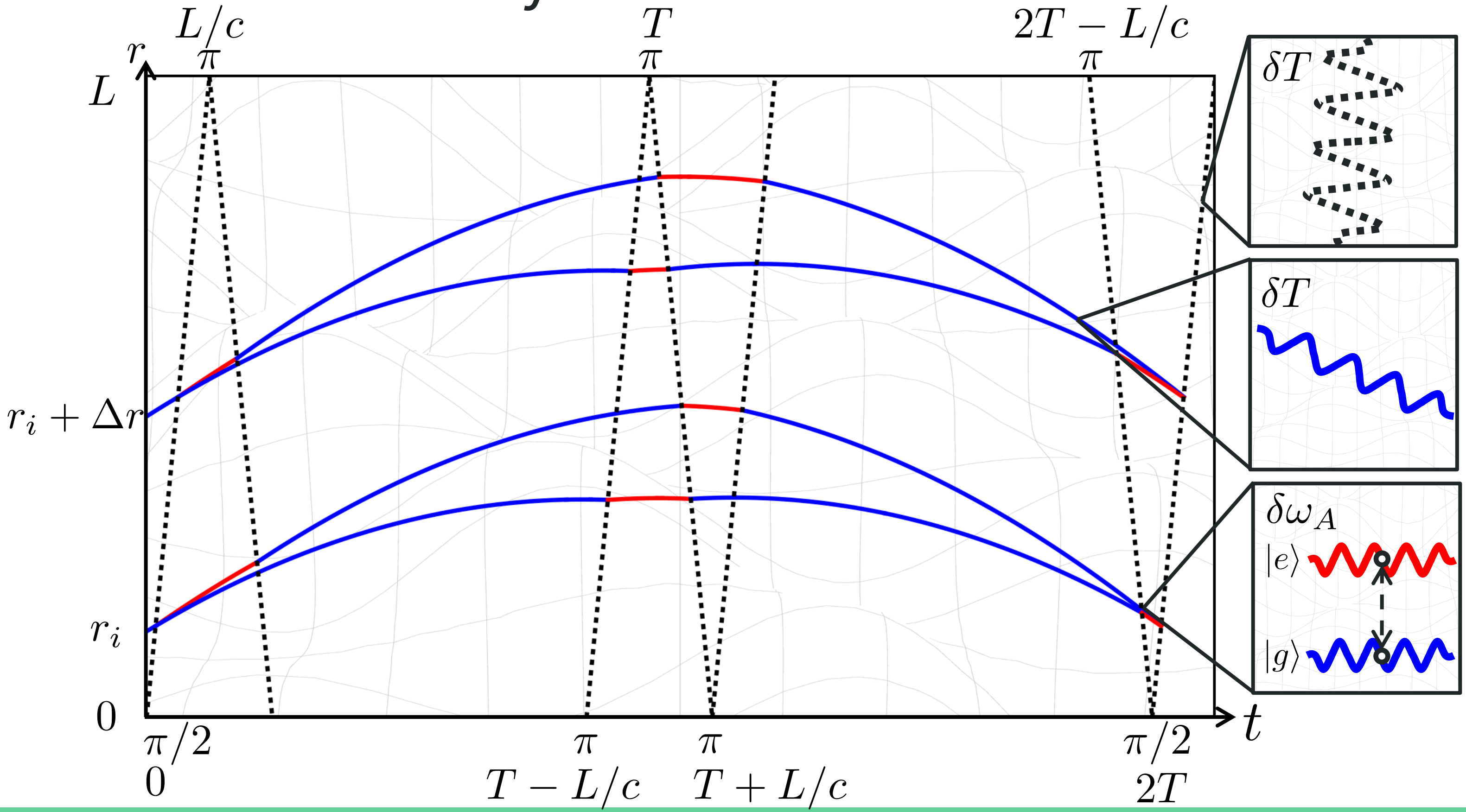
$$\mathcal{H} = \sqrt{\rho_{\mathrm{DM}}} \left(\frac{\alpha^{(0)}}{\Lambda} X(t) + \frac{\alpha^{(1)}}{\Lambda} v_A^i V_i(t) + \frac{\alpha^{(2)}}{\Lambda} v_A^i v_A^j M_{ij}(t) \right) m_A \delta^{(3)}(\vec{x} - \vec{x}_A(t))$$

$$+ \sqrt{\rho_{\mathrm{DM}}} \left(\frac{\beta^{(0)}}{\Lambda} (F^2 Y_1(t) + F_{0i} F^{0i} Y_2(t)) + \frac{\beta^{(1)}}{\Lambda} F_{\sigma 0} F^{i\sigma} W_i(t) + \frac{\beta^{(2)}}{\Lambda} F^{i\sigma} F_\sigma^j N_{ij}(t) \right)$$

Light couplings

D. Blas, J. Carlton, C. McCabe. arXiv: 2412.14282

Three sensitivity channels!



Laser propagation delay (tensor)

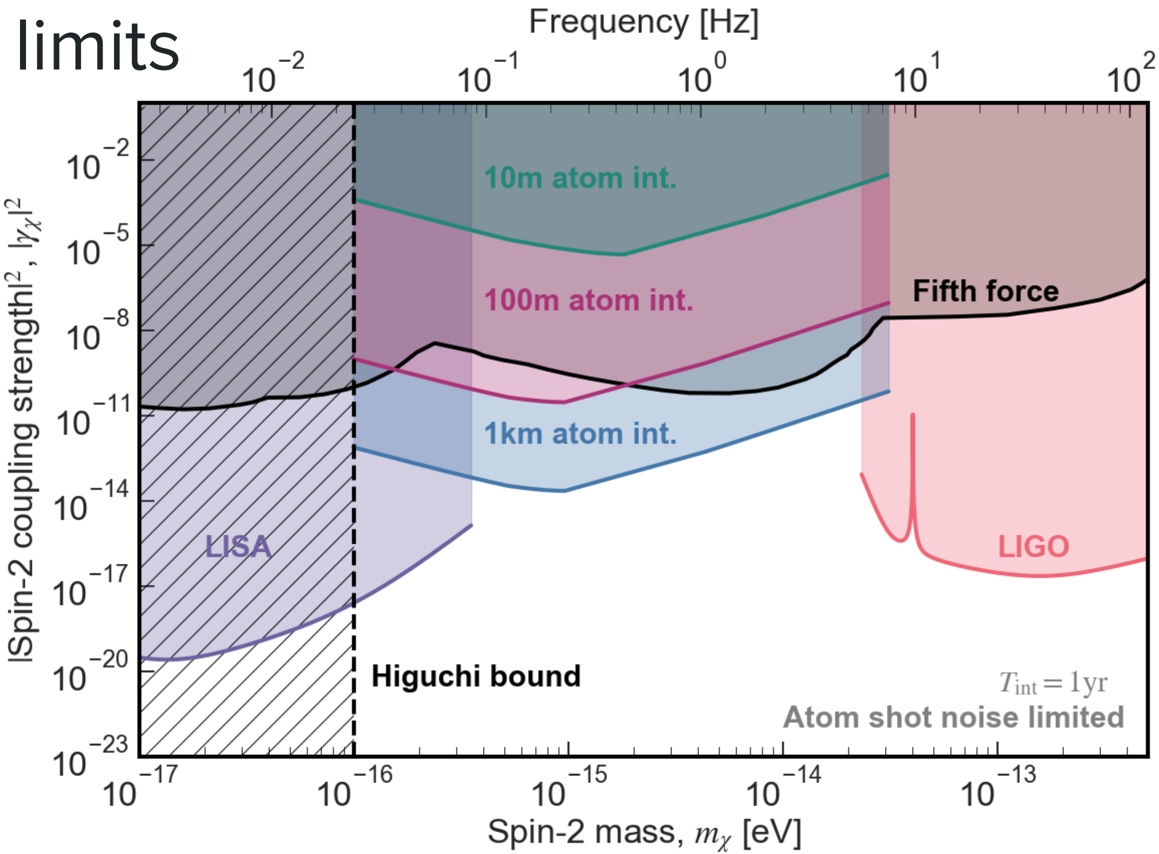
Atom propagation delay (vector)

Electron energy level modification (scalar)

Projected detection limits

10m, 100m and 1km example atom interferometers

Isotope	L [m]	T [s]	n	Δr [m]	S_n [Hz^{-1}]
^{87}Sr	10	0.74	1000	5	10^{-8}
^{87}Sr	100	1.4	1000	90	10^{-10}
^{87}Sr	1000	1.4	1000	980	0.09×10^{-10}



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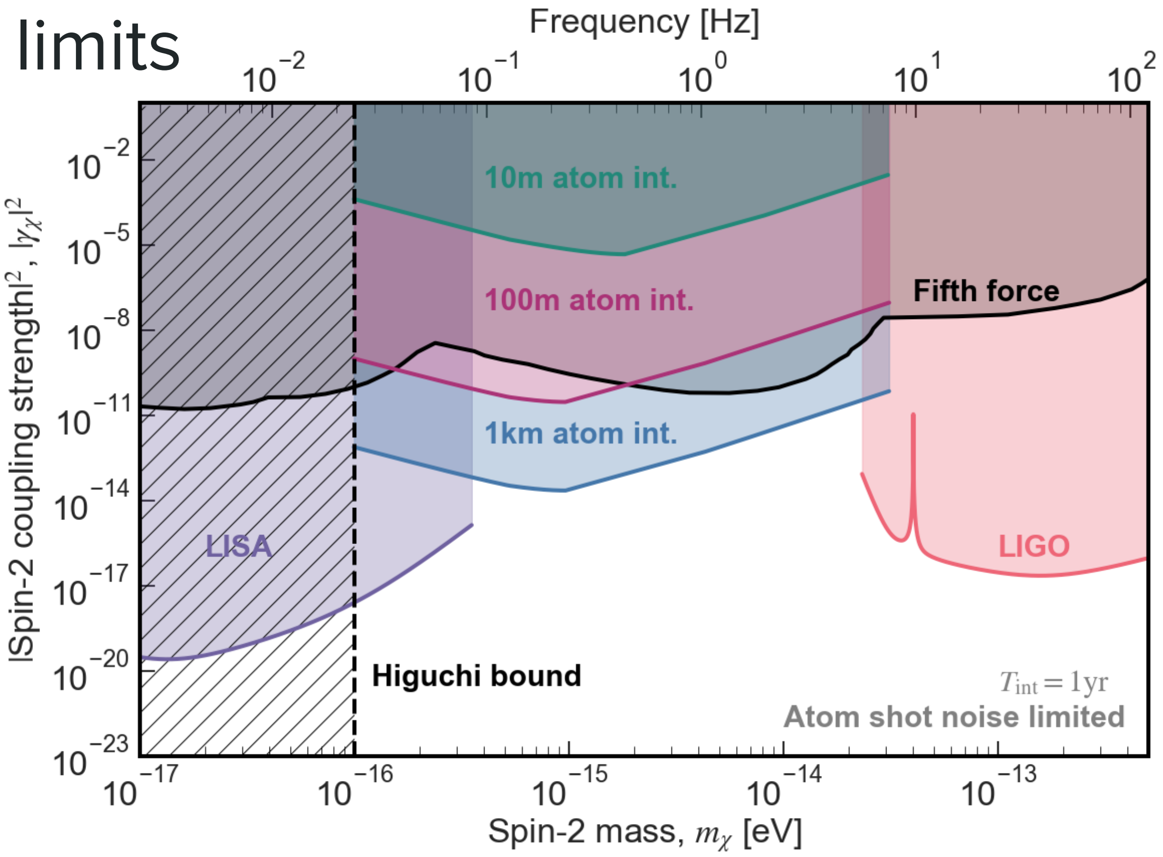
Projected detection limits

10m, 100m and 1km example atom interferometers

Generic coupling gamma

$$\gamma_\chi = \alpha^{(i)}, \beta^{(j)} \quad \text{for all } i, j$$



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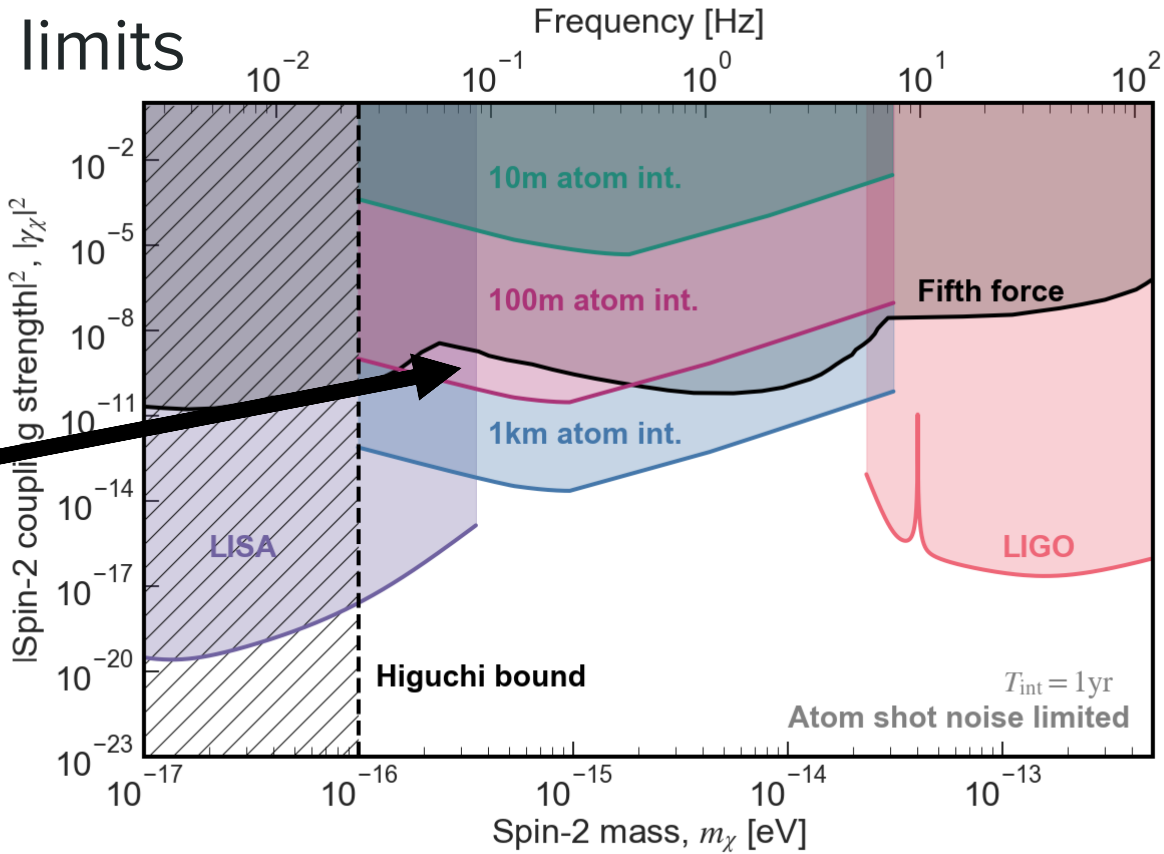
Projected detection limits

Leading constraints on scalar mode come from ‘fifth force’ experiments

$$\delta V_{\mathrm{Newt}} \propto (\alpha^{(0)})^2 e^{-m_s r}$$

In this range, from lunar laser ranging



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Projected detection limits

Leading constraints on scalar mode come from ‘fifth force’ experiments

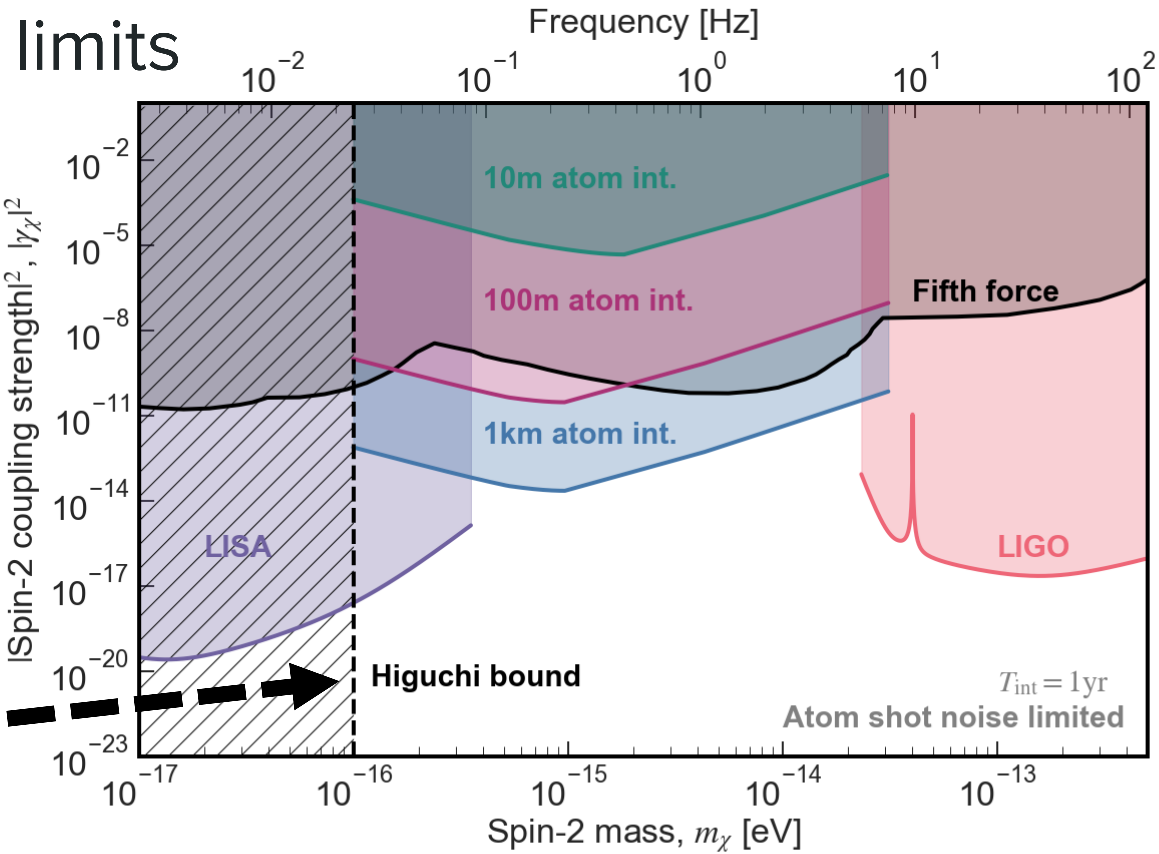
$$\delta V_{\text{Newt}} \propto (\alpha^{(0)})^2 e^{-m_s r}$$

In this range, from lunar laser ranging

Higuchi bound sets a lower bound for mass of spin-2 field

$$m^2 \geq 2H^2$$

Least stringent bound from BBN



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Advantages of networking!

AION plans to network with MAGIS-100 to enhance sensitivity in ULDM/GW searches.

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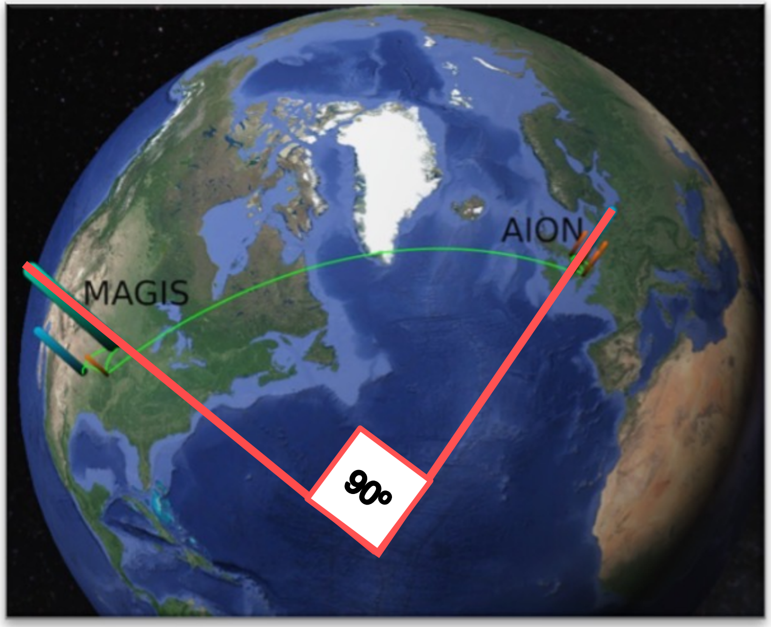
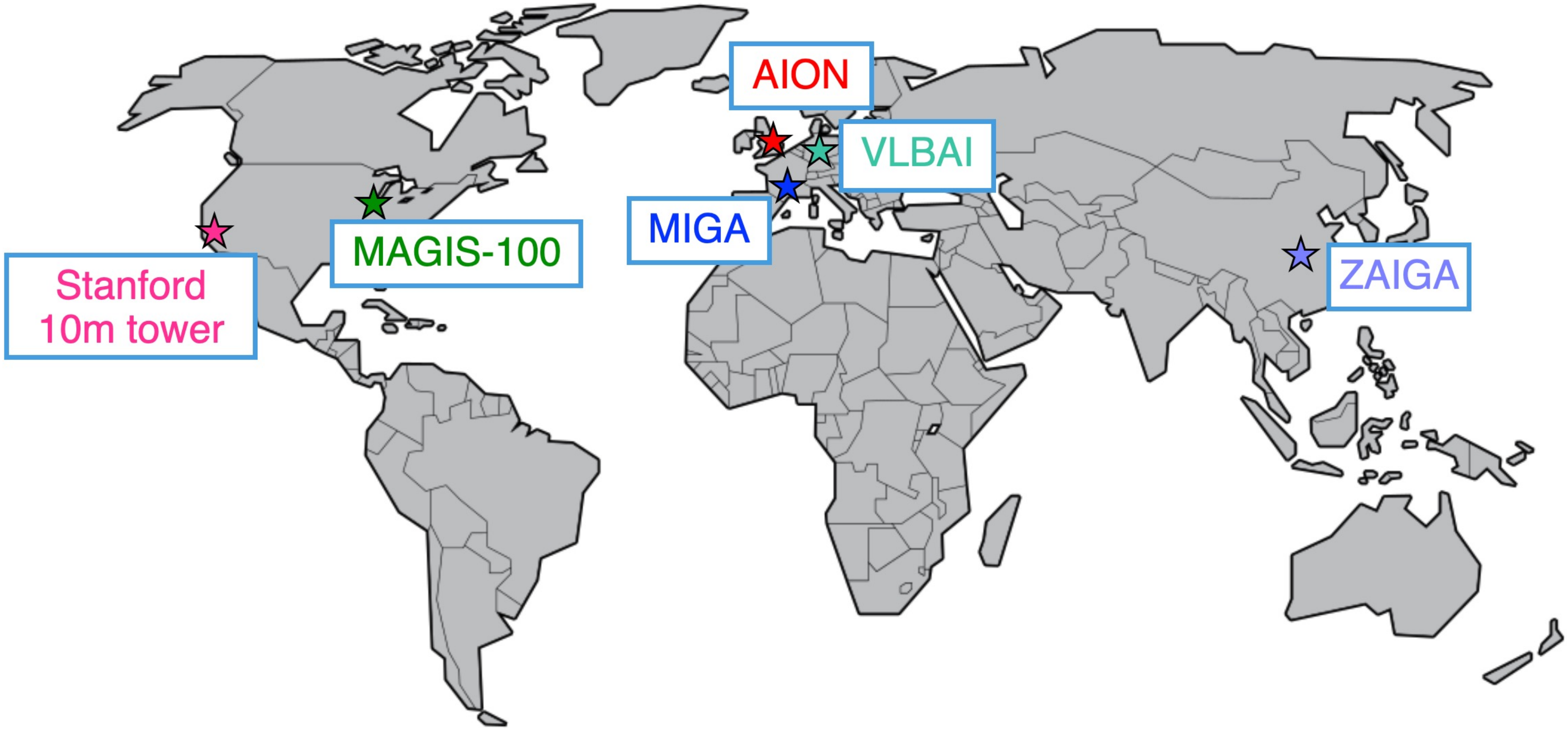
$$\varphi_{ij}^{\mathrm{TT}}(t,\mathbf{x}) = \sum_{\lambda} \varphi_{0,\lambda}^{\mathrm{TT}} e_{ij}^{\lambda}(\mathbf{k}_t)\cos(\omega_t t - \mathbf{k}_t \cdot \mathbf{x})$$

Distinguish dark matter models through directional dependence.



Progress towards a global network!



Terrestrial very-long baseline atom interferometry workshop summary: arXiv: 2310.08183

Summary

AION is an upcoming atom interferometer experiment, using quantum sensors for detecting ultralight dark matter and gravitational waves – in the 'mid-band' between LISA and LIGO.

Spin-2 ULDM can be probed by gravitational wave detectors – however, atom interferometers can detect it through several different channels without altering any of the experimental design! Other GW/ULDM experiments may also detect other couplings not probed by atom interferometers.

A global network of atom interferometers will enhance these searches further, probing the directional dependence of the field and other couplings.

D. Blas, J. Carlton, C. McCabe. arXiv: 2412.14282

Backup

Matter couplings

	FP	LV1	LV2
$\alpha^{(0)}X(t)$	$-\alpha_{\rm FP}^{(2)}v_{\rm DM}^2\frac{\sqrt{\frac{8}{3}f_s}}{m}\cos(\phi_s(t))$	0	$\alpha_{\rm LV}^{(0)}\frac{\sqrt{\frac{8}{3}f_s}}{m_s}\left(\alpha^{-1}+\lambda_{\rm at}\right)\cos(\phi_s(t))$
$\alpha^{(1)}V_i(t)$	$-2\frac{\alpha_{\rm FP}^{(2)}}{m}\left[v_{{\rm DM},\,i}\sqrt{\frac{8f_s}{3}}\cos(\phi_s(t)) + v_{\rm DM}\sqrt{\frac{f_v}{2}}\sum_\lambda e_i^\lambda\cos(\phi_v(t))\right]$	0	$\alpha_{\rm LV}^{(1)}\frac{\sqrt{\frac{2}{3}f_s}}{m_s}\frac{\hat{v}_{{\rm DM},i}}{v_{\rm DM}}\frac{1+\lambda}{\lambda+\beta}\cos(\phi_s(t))$
$\alpha^{(2)}M_{ij}(t)$	0	$\frac{\alpha_{\rm LV}^{(2)}}{m_t}v_A\sum_\lambda e_{ij}^\lambda\sqrt{f_t}\cos(\phi_t(t))$	0

Light couplings

	FP	LV1	LV2
$\beta^{(0)}Y_1(t)$	0	0	$\beta_{\rm LV}^{(0)}\frac{\sqrt{\frac{8}{3}f_s}}{m_s}\left(-\alpha^{-1}+\lambda_{l1}\right)\cos(\phi_s(t))$
$\beta^{(0)}Y_2(t)$	$\beta_{\rm FP}^{(2)}\frac{v_{\rm DM}^2}{m}\sqrt{\frac{8}{3}f_s}\cos(\phi_s(t))$	0	$\beta_{\rm LV}^{(0)}\frac{\sqrt{\frac{8}{3}f_s}}{m_s}\left(4\alpha^{-1}+\lambda_{l2}\right)\cos(\phi_s(t))$
$\beta^{(1)}W_i(t)$	0	0	$\beta_{\rm LV}^{(1)}\frac{\sqrt{\frac{2}{3}f_s}}{m_s}\frac{\hat{v}_{{\rm DM},i}}{v_{\rm DM}}\frac{1+\lambda}{\lambda+\beta}\cos(\phi_s(t))$
$\beta^{(2)}N_{ij}(t)$	$\frac{\beta_{\rm FP}^{(2)}}{m}\Big((\delta_{ij}-3\hat{v}_{{\rm DM}\,i}\hat{v}_{{\rm DM}\,j})\sqrt{\frac{2}{3}f_s}\cos(\phi_s(t)) - \hat{v}_{{\rm DM}\,i}\sum_\lambda e_j^\lambda\sqrt{2f_v}\cos(\phi_v(t)) + \sum_\lambda e_{ij}^\lambda\sqrt{f_t}\cos(\phi_t(t))\Big)$	$\frac{\beta_{\rm LV}^{(2)}}{m_t}\sum_\lambda e_{ij}^\lambda\sqrt{f_t}\cos(\phi_t(t))$	$\beta_{\rm LV}^{(2)}\left[\sum_\lambda e_{ij}^\lambda\frac{\sqrt{f_t}}{m_t}\cos(\phi_s(t)) + (\delta_{ij}-\hat{v}_i\hat{v}_j)\frac{\sqrt{2/3f_s}}{m_s}\cos(\phi_t(t))\right]$

Spin-2 sensitivity

$$\Delta\Phi = \sum_\chi \Delta\Phi_\chi = \sum_\chi 4\gamma_\chi \frac{\omega_{A,0}}{\Lambda} \frac{\sqrt{\rho_{\rm DM}}}{m_\chi^2} \frac{\Delta r}{L} \sin\left[\frac{m_\chi n L}{2}\right] \sin\left[\frac{m_\chi T}{2}\right] \sin\left[\frac{m_\chi (T-(n-1)L)}{2}\right] \cos\left[m_\chi \frac{2T+L}{2} + \phi_\chi\right]$$

γ_χ	**FP**	**LV1**	**LV2**
$\alpha^{(0)}$	$-\alpha^{(0)} v_{\rm DM}^2 \frac{8\sqrt{2f_s}}{\sqrt{3}}$	0	$\alpha^{(0)} \frac{8\sqrt{2f_s}}{\sqrt{3}} (\alpha^{-1} + \lambda_{\rm at})$
$\beta^{(0)}$	$\beta^{(0)} v_{\rm DM}^2 \frac{8\sqrt{2f_s}}{\sqrt{3}}$	0	$\beta^{(0)} \frac{8\sqrt{2f_s}}{\sqrt{3}} (3\alpha^{-1} + \lambda_{l1} + \lambda_{l2})(2+\xi_A)$
$\alpha^{(1)}$	$-2\alpha^{(1)} v_{\rm DM} D^i \left[\hat{v}_{{\rm DM},\,i} \sqrt{\frac{8f_s}{3}} + \sqrt{\frac{f_v}{2}} \sum_\lambda e_i^\lambda\right]$	0	$\alpha^{(1)} \frac{2\sqrt{f_s}}{\sqrt{3}} D^i \frac{\hat{v}_{{\rm DM},i}}{v_{\rm DM}} \frac{1+\lambda}{\lambda+\beta}$
$\beta^{(1)}$	0	0	0
$\alpha^{(2)}$	0	0	0
$\beta^{(2)}$	$\beta^{(2)} D^{ij} \Big[(\delta_{ij} - 3\hat{v}_{{\rm DM},i}\hat{v}_{{\rm DM},j})\sqrt{f_s} + \sqrt{f_t}\sum_\lambda e_{ij}^\lambda - \sqrt{f_v}\hat{v}_{{\rm DM},i}\sum_\lambda e_j^\lambda\Big]$	$\beta^{(2)} \sqrt{f_t} \sum_\lambda D^{ij} e_{ij}^\lambda$	$\beta^{(2)} D^{ij} \Big[\sqrt{f_t}\sum_\lambda e_{ij}^\lambda + \frac{2\sqrt{f_s}}{\sqrt{3}}(\delta_{ij} - \hat{v}_{{\rm DM},i}\hat{v}_{{\rm DM},j})\Big]$

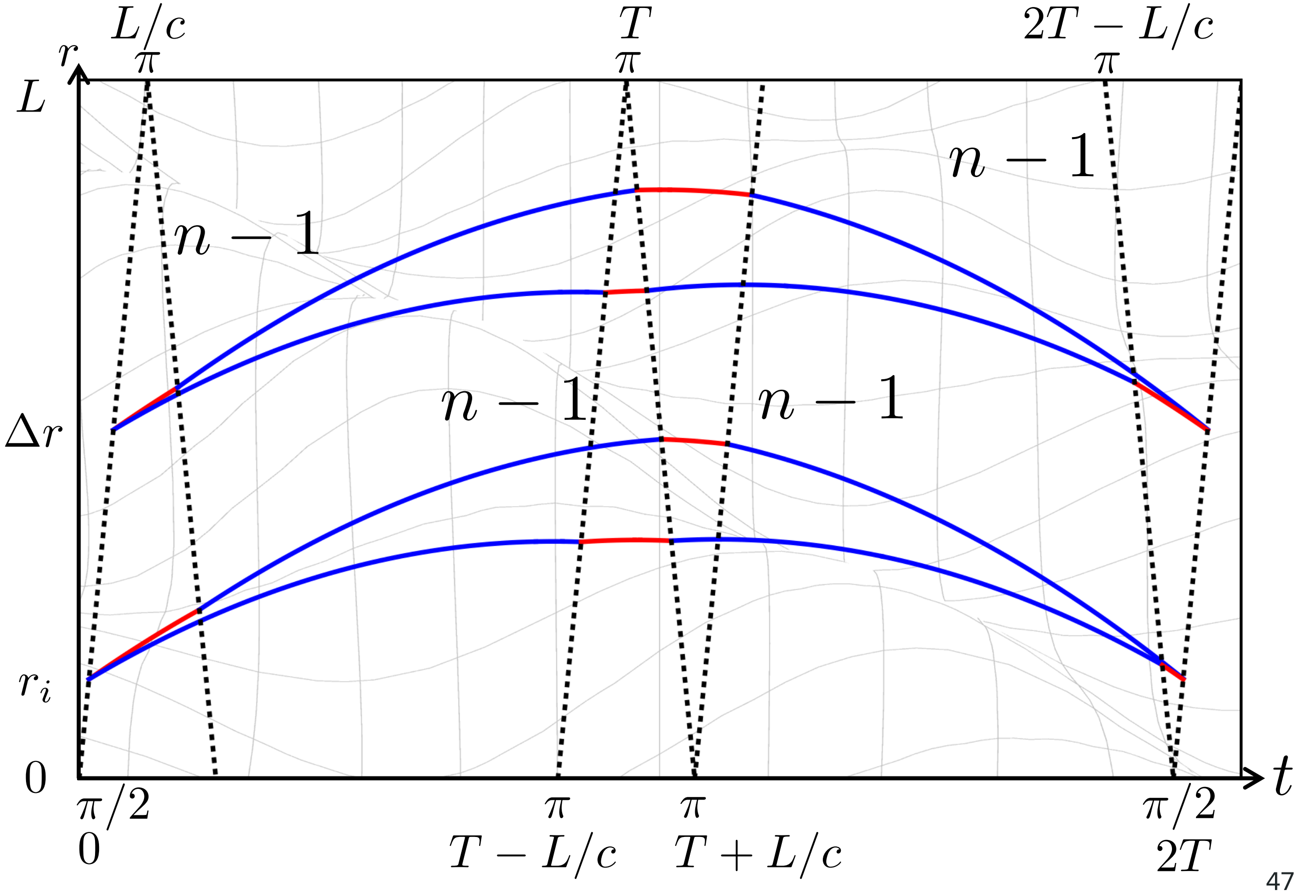
LMT pulses

Additional pulses enhance sensitivity

$$n = 2$$

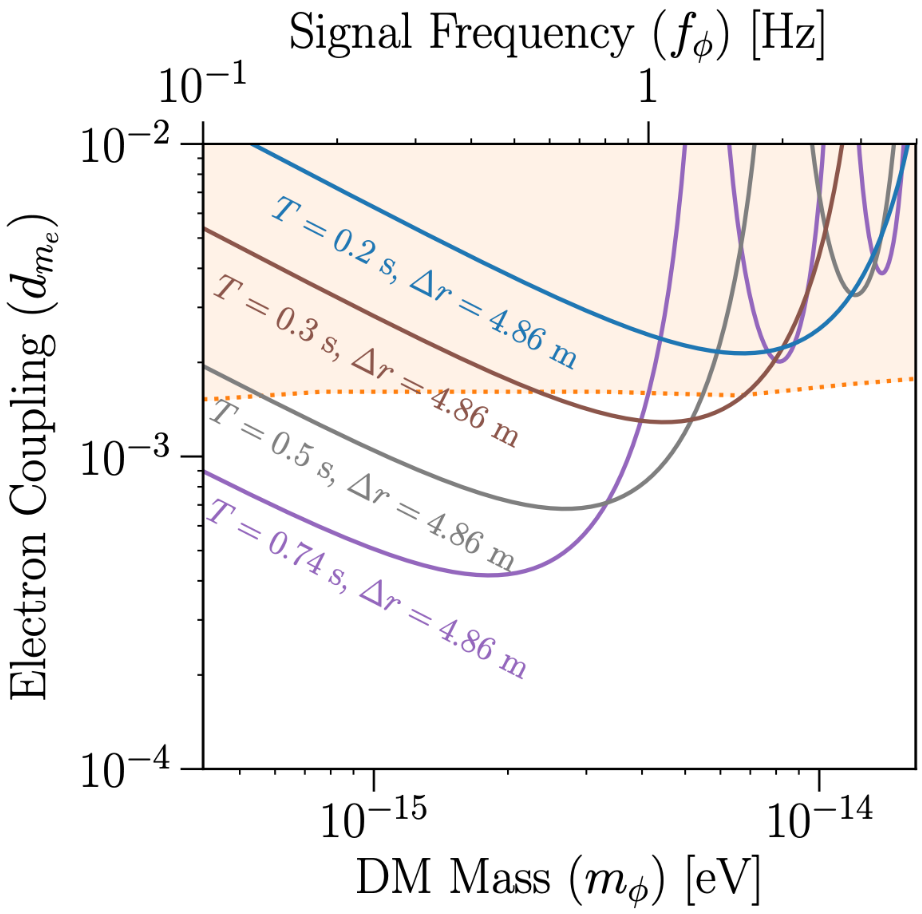
Atom gradiometer

$$\Delta\phi = \phi_1 - \phi_2$$



Scalar ULDM sensitivity

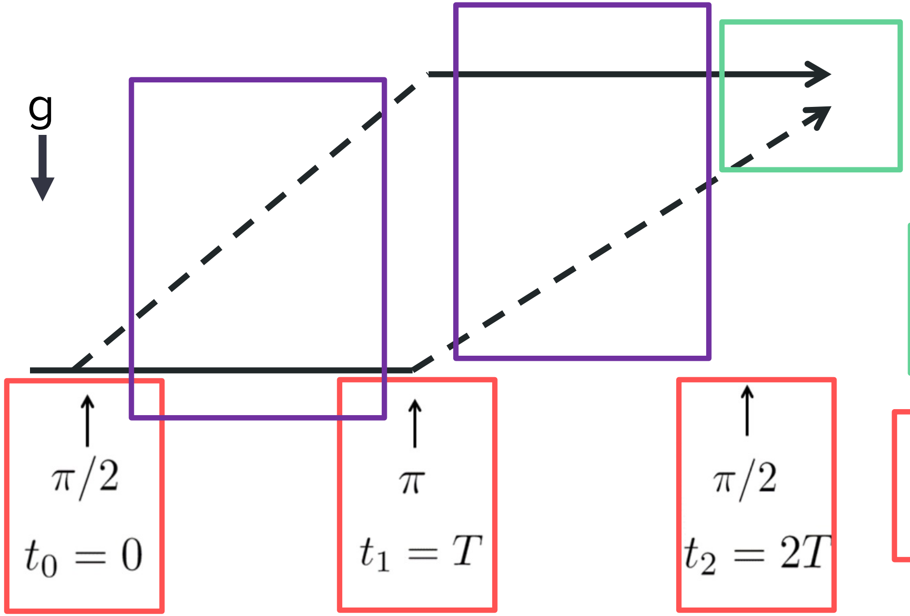
- *ULDM mass/frequency sensitivity depends on T.*



L. Badurina, D. Blas, C. McCabe. arXiv: 2109.10965

Phase shifts

$$\phi = \phi_{\text{prop}} + \phi_{\text{sep}} + \phi_{\text{laser}} = kgT^2$$



$$\phi_{\text{prop}} = \frac{1}{\hbar}\left[\sum_u \left(\int_{ti}^{tf} (L_c - E_i)\mathrm{d}t\right) - \sum_l \left(\int_{ti}^{tf} (L_c - E_i)\mathrm{d}t\right)\right]$$

$$\phi_{\text{sep}} = \frac{1}{\hbar}\bar{\boldsymbol{p}} \cdot \Delta \boldsymbol{z}$$

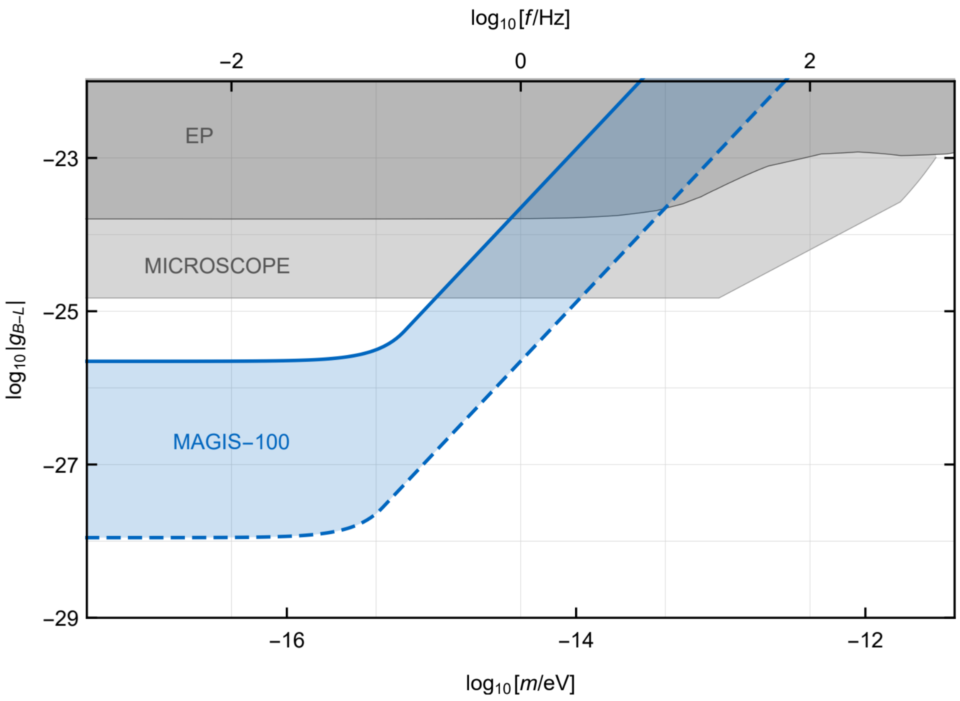
$$\phi_{\text{laser}} = \left(\sum_j \pm\phi_L(t_j, \boldsymbol{z}_u(t_j))\right)_u - \left(\sum_j \pm\phi_L(t_j, \boldsymbol{z}_l(t_j))\right)_l$$

Spin-1 dark matter

B-L coupling, which generates a 'dark' electric field

$$\Delta F_{B-L} \sim g_{B-L} \left(\frac{Z_1}{A_1} - \frac{Z_2}{A_2} \right) E_{B-L}$$

Probe with a dual-species interferometer



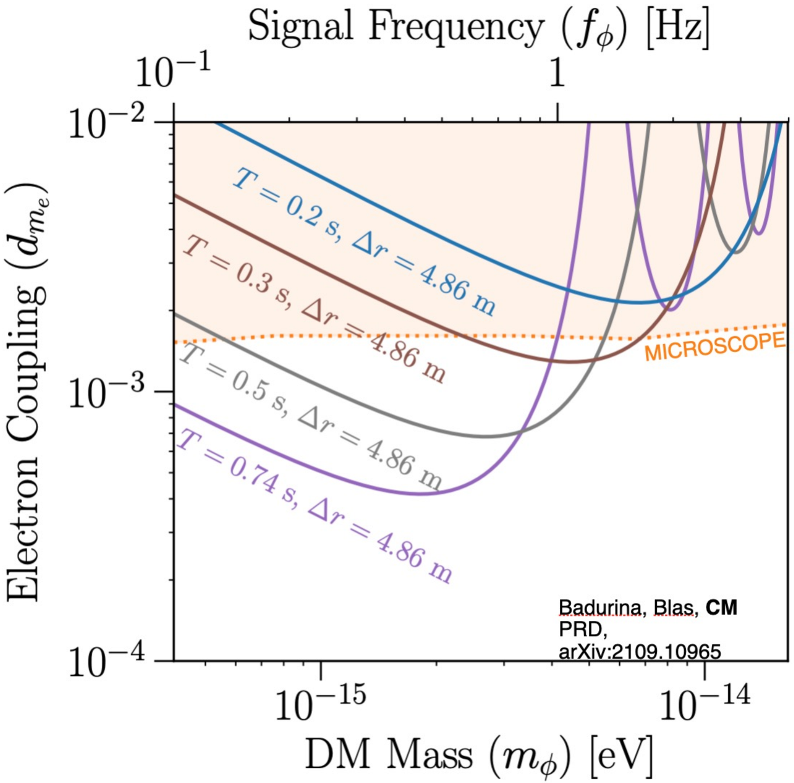
M. Abe et al. arXiv: 2104.02835

AION-10 sensitivity projections

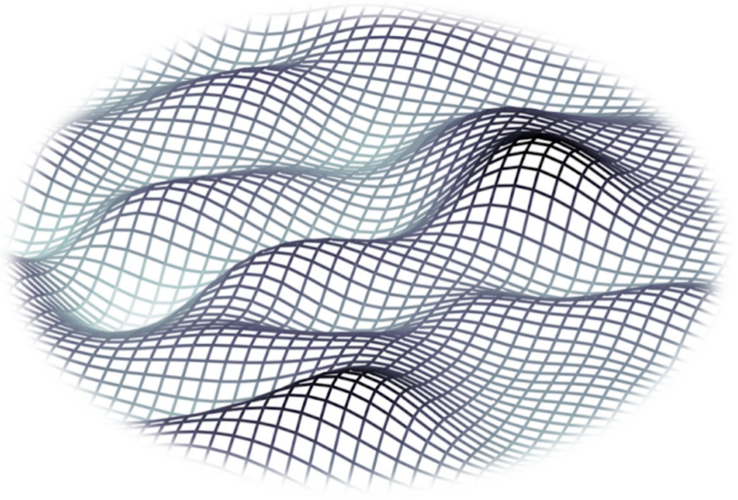
$$d_{m_e}^{\text{best}} \sim \left(\frac{1}{T}\right)^{5/4} \frac{1}{C\, n \Delta r} \left(\frac{\Delta t}{N_a}\right)^{1/2} \left(\frac{1}{T_{\text{int}}}\right)^{1/4}$$

Handles to optimise (in order of priority):

T ~ 1s (interrogation time)
C ~ 0.1 - 1 (constrast)
n ~ 1000 (LMT)
Δr ~ AI separation
Δt ~ sampling time
$N_a \sim$ atoms in cloud
$T_{\text{int}} \sim 10^7\text{s}$ (integration time)



Massive gravity field theory



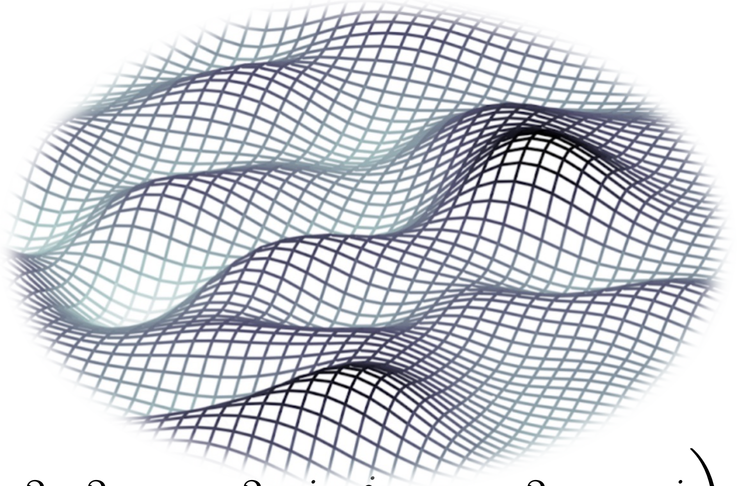
Let's consider a massive spin-2 ultra-light field $\varphi_{\mu\nu}$

Fierz-Pauli Lagrangian

$$\mathcal{L}_{\rm FP} = \mathcal{L}_{\rm EH} - \frac{1}{4}m^2\left(\varphi_{\mu\nu}\varphi^{\mu\nu} - \varphi^2\right)$$

Lorentz invariant massive spin-2 field

Massive gravity field theory



Let's consider a massive spin-2 ultra-light field $\varphi_{\mu\nu}$

$$\mathcal{L}_{\mathrm{FP}} = \mathcal{L}_{\mathrm{EH}} - \frac{1}{4}\Big(m_0^2\varphi_{00}^2 + 2m_1^2\varphi_{0i}^2 - m_2^2\varphi_{ij}^2 + m_3^2\varphi_i^i\varphi_j^j - 2m_4^2\varphi_{00}\varphi_i^i\Big)$$

Lorentz violating massive spin-2 field